SEDIMENT DYNAMICS ON WEMYSS BEACH, SOUTH FIFE

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Thesis submitted to the University of St Andrews for the Degree of Master of Philosophy in the Department of Geology.

1st April 1997

DECLARATIONS

(i) I, Kathryn Ann Miller, hereby certify that this thesis, which is approximately 40,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

28 March 1997

(ii) I was admitted as a research student in October 1995 and as a candidate for the degree of M.Phil in October 1995; the higher study for which this is a record was carried out in the University of St. Andrews between 1995 and 1997.

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(iii) I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of M.Phil in the University of St. Andrews and that the candidate is qualified to submit this thesis in application for that degree.

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ABSTRACT

The beaches of South Fife consist of an unusual mix of heterogeneous pebbles, sand and coal waste, and consequently provide a complex environment in which to examine sediment transport.

The use of tracers revealed that low density coal pebbles were 'rejected' from the bedload layer of ironstone and sandstone pebbles, and were transported to extreme distances alongshore and potentially offshore. Whereas, the high specific gravity of the ironstone pebbles restricted longshore transport, but enhanced movement in the backwash to low water.

Coarse pebbles protruded from the mixed bed of closely packed small pebbles and generated turbulence, thus enhancing the lift forces for entrainment. Once in transport, the coarse pebbles 'overpassed' the small pebbles. Therefore, 'Selective transport' according to pebble composition and size, was an important phenomenon on the mixed beach.

On the mixed beach, the sand was readily moved offshore in the backwash and transported by longshore currents. Whereas, pebble transport was restricted to the swash and backwash, in the direction of maximum wave energy. Pebbles were either buried in the sand or lay flat on the surface. The limited protrusion of the pebbles lowered the shear stress available for pebble entrainment. Furthermore, once in motion the sand absorbed the impacts of the saltating pebbles.

Vertical cores were used to investigate the structure of the beach. This technique revealed that a homogenous upper layer of coarse pebbles was transported along and upshore, over a less mobile beach layer of compacted poorly sorted sediment. Dense ironstone pebbles armoured the beach face and trapped finer sediments below. Consequently, a mix of sediment and dense coarse pebbles could be used to increase beach stability.

Important factors influencing the dynamics of pebbles on mixed beaches were identified, however an adequate formula for mixed sediment transport remains to be calibrated.

1:1 INTRODUCTION

Currently our understanding of coastal sediment transport is based upon research examining sand beaches which form most of our mobile coastline. Although less common, a shingle beach represents a more dynamic landform and in recent years it has been recognised that there is insufficient information regarding sediment transport on shingle beaches. Shingle is defined as sedimentary particles between 2 and 256 mm in diameter on the Wentworth scale. The term 'pebble' is also commonly applied to particles of this size. The smallest pebbles, of 2-4 mm diameter, are often referred to as granules. In addition to size, the physical form of the pebbles includes composition, density and shape. These form parameters are not independent of each other and control the hydrodynamic behaviour of the pebbles in the nearshore zone. Consequently, many general assumptions made from the research on sand beaches are not applicable to pebble beaches.

Pebble beaches are susceptible to great change, as a result of periodic storms, sea level changes, sediment supply and human activities. Along the South coast of England there is growing concern over the depletion and landward migration of pebble beaches. At the same time renourishment of beaches with pebbles is proving to be a successful type of coastal protection, as a pebble beach functions as a natural buffer. Therefore, an assessment of the relationship between wave energy and the resultant pebble transport is essential if effective coastal management strategies are to be formulated and executed.

Furthermore, the research available on shingle beaches has only considered homogenous pebble beaches. The research has neglected mixed beaches composed of heterogeneous pebbles with a variable proportion of sand, consequently no longshore sediment transport quantification has been attempted. Kirk (1980) described mixed beaches as;

"Morphologically distinct and dynamically complex".

The stability of shingle beaches used for coastal protection could be potentially enhanced by introducing a greater diversity of sediment size. Therefore, to gain greater insight into the sediment dynamics on mixed beaches the overall aim of this research was to investigate the response of pebbles and sand in wave action on a mixed beach. To achieve this aim the following objectives were proposed;

RESEARCH AIMS

- To assess the transport rate and direction of pebbles of different composition and size.
- To assess the response of sand in wave action on the mixed beach.
- To examine the response of pebbles in wave action, when a high proportion of sand composed the mixed beach.

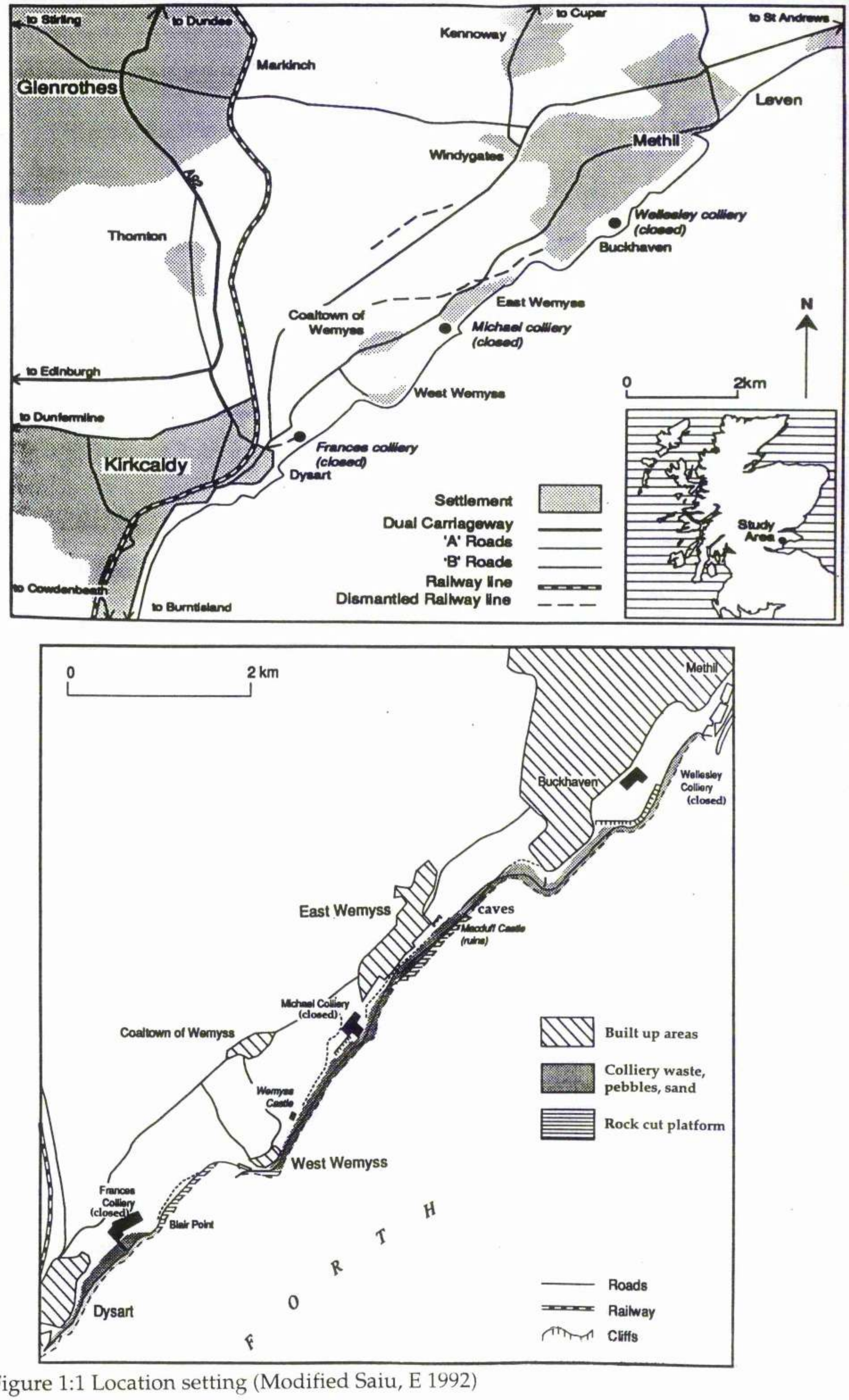


Figure 1:1 Location setting (Modified Saiu, E 1992)

•To correlate the transport of the sand and pebbles to the wave and tidal conditions.

•To investigate the vertical structure and the depth of disturbance of the mixed beach foreshore, to gain insight into the stability of the mixed beach.

•To determine the validity of the CERC longshore sediment transport formula on the mixed beach (Coastal Engineering Research Center).

Before these research aims were applied the physical wave processes and the basic principles of sediment entrainment and transport mechanisms were examined. From the literature reviewed it was determined that a tracer technique would be the most appropriate means of investigating transport on the mixed beach. Tracers enabled the behaviour of individual pebbles of different compositions to be monitored on a tide by tide basis and directly related to the wave parameters. Furthermore, the deployment of tracers assessed how wave and sediment dynamics interacted temporally and spatially.

RESEARCH SETTING

The South Fife coastline that borders the Firth of Forth, provides an ideal setting in which to investigate sediment transport on a mixed beach (figure 1:1). The Northeast-Southwest trending foreshore that extends from East Wemyss to the rocky promontory at West Wemyss encloses a beach composed of an unusual mix of pebbles, with a variable proportion of sand (plate 1:1). A previous investigation on sediment transport and coastline changes along this foreshore was undertaken by R.H Cuthbertson and Partners in association with HR Wallingford in 1994. Interest in the transport dynamics on this beach arose following the bad storms in the winter of 1994, as it was recognised that the sea had advanced by up to 10 metres in front of East Wemyss, since September of the previous year. Erosion is not a new phenomena along the South coastline of Fife, as the Firth of Forth is susceptible to severe storm waves generated in the North sea, which are channelled between May Island and Bass rock. However, over the last ten years, dramatic and serious changes have been witnessed along the Southeast coastline of Fife between Methil and Dysart, where past coal mining activities have led to unprecedented modification of the coastline (plate 1:2).

By the late 19th century the Wellesley, Michael and Frances collieries bordered and extended beneath the Firth of Forth, yielding large quantities of wastes, in the form of unrecovered coal, clinker, loose refractory brick, shale and sandstone. This material was dumped in coal bings (spoil heaps) along the shoreline which acted as new sediment supplies feeding the dominant southwestward longshore drift. The availability of sediment during mining caused a seaward migration of the watermark positions, as the beaches built out from the former cliff line. At the same time the deep mine workings were the cause of local subsidence. A fall in land level as a result of the subsidence allowed a relative local rise in sealevel.

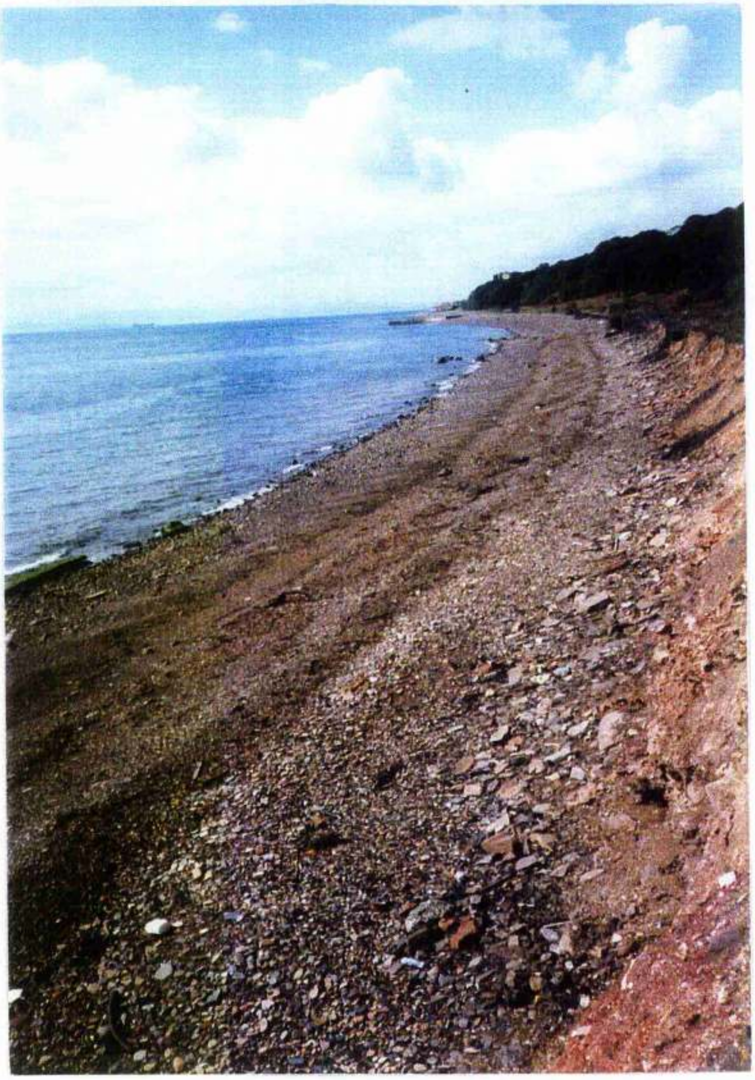


Plate 1:1 East Wemyss Mixed Beach.

Plate 1:2 The impact of coal mining activities on the mixed beach.

While mining prevailed the build up of the coal waste along the coast disguised the effects of subsidence.

Progressive closure of the mines from 1967 until 1984 lead to the cessation of the supply of colliery waste to the beaches and what had built up on the beaches has since been progressively removed by the sea, to reveal the effects of mining subsidence. Research undertaken by Saiu and McManus (1996) established that the sections of the coastline that are experiencing severe erosion correlate to mine workings where the most coal has been extracted. Along the coastline between Buckhaven and East Wemyss up to 5.5 metres of subsidence has been quantified and the important archaeological Wemyss caves have been lowered by 1-2 metres. The local segments of the coastline lowered by mining subsidence are exposed to new erosion as the beaches are reverting to positions landward of the premining coastline (plate 1:3). Furthermore, the erosion problem at East Wemyss is strongly related to the reduction in the supply of fresh sediment from the Wellesley colliery bing, that is now protected by heavy rip rap armouring to prevent sediment loss. This investigation provides a detailed review of how the beach sediment and colliery waste responds in wave action, which is essential before further coastal protection strategies can be planned with confidence.

THESIS OUTLINE

The report begins with a description of the physical setting, with information on waves and tidal currents. This is followed by an appraisal of the literature available on pebble transport. Attention is turned to a brief outline of the physical wave and tidal processes responsible for the initiation of sediment transport. A more detailed review is then made of the tracer techniques available and the longshore transport formula used in this investigation.

Chapter 6 focuses on the main tracer pebble experiment, which examines the response of pebbles of different composition in wave action. The disturbance of the mixed beach face is examined in Chapter 7. As a consequence of the findings in the tracer surveys, additional smaller experiments were undertaken to examine the response of fine pebbles and sand in wave action, on the mixed beach. Finally, the influence of the vertical beach structure on the transport of pebbles and sand was examined.

The final chapter includes a summary of the main conclusions arising from the various experiments and an appraisal of the validity of an empirical longshore transport formula. Suggestions are made as to appropriate modifications in the formula for application on a mixed beach. In conclusion, the sediment dynamics are considered in the light of the stability of the coastline.

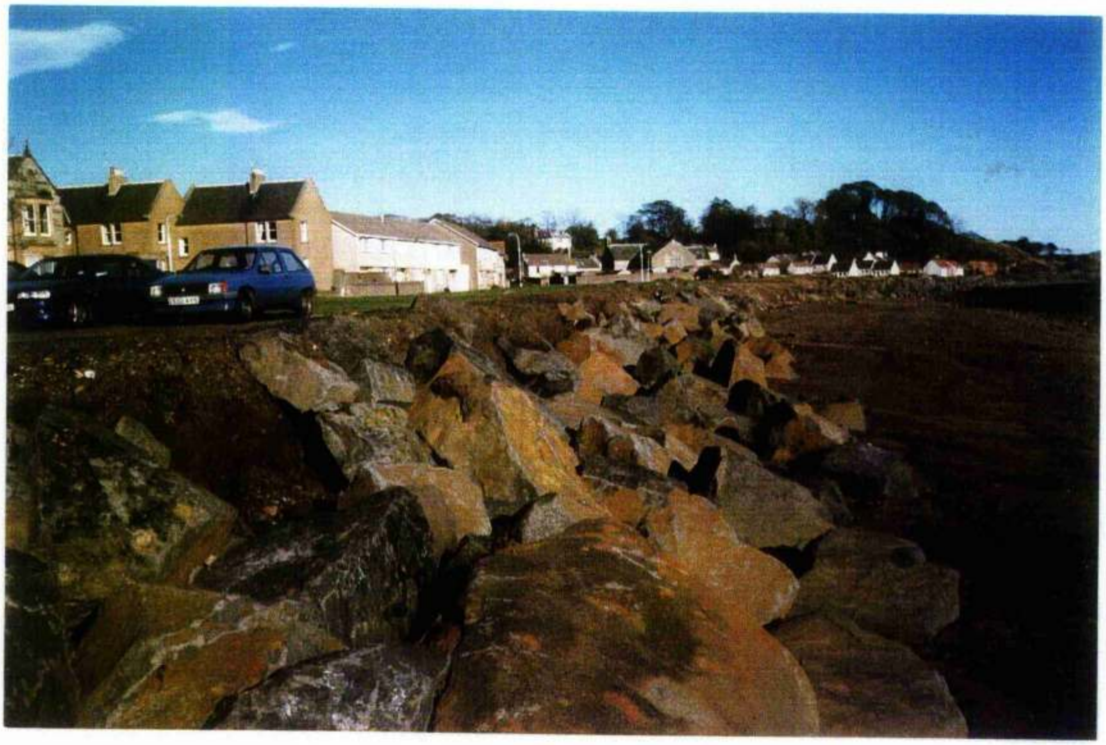


Plate 1:3 Erosion due to the impact of coal mining.

Plate 2:1 Terrace of unconsolidated coal waste at the Michael Headland.

2:1 PHYSICAL SETTING

The Firth of Forth extends for approximately 100km eastwards from Stirling to the North Sea. Most of the Firth of Forth is shallow (<20m), with extensive shelf areas at Largo and Aberlady Bay. In the centre of the Firth of Forth deep narrow channels reach depths of 65 metres below O.D. (Admiralty Chart 734). The surface expression of the estuary and the geomorphology of the area are products of Quaternary glacial events, when ice originated in the Grampian highlands and flowed eastwards. The final retreat of the glaciers took place in stages, interrupted with periods of readvance. Each ice advance and decay was associated with a change in sea level. Raised beaches and drift deposits indicate that the sea level was formerly higher than it is at present. At East Wemyss, caves are excavated in the 50 metre high cliffs of the former shoreline. A raised beach platform, that is 3 metres above the High Water Mark, extends in front of the cliffs.

The solid Geology of the cliffs and the rock platform are composed of cyclic sequences of Carboniferous sedimentary rocks, consisting of diagnostic red, brown micaeous sandstones, intercalated with siltstones, shales and coal. Together these rocks form part of the Upper Coal Measures Sequence, the coal seams formed the basis of the economic wealth of this area. The low terraced coast edge fronting East Wemyss village is reclaimed land from the accretion of mining waste. The terrace of unconsolidated waste extends along the coastline to the Michael headland that marks the position of the former Michael colliery (plate 2:1). This promontory projects directly to the high water mark and erosion is currently reworking the outer limit of the colliery waste.

The beach is composed of a pebbles which range in size from granules to cobbles. At places only a thin veneer of sediment covers the bedrock below. The pebbles are of mixed composition, as a result of erosion of local outcrops of the Upper Coal Measures Sequence and the reworking of glacial drift deposits. The dense ironstone pebbles were nodules previously located within the Coal Measures. A range of igneous compositions and volcanic agglomerate were transported from further North and a supply of dolerite and granite can be attributed to discarded ballast from ships. In addition, a large proportion of the sediments are derived from the undermining of the unconsolidated colliery waste terraces that border the shoreline. The colliery waste consists of coal, clinker and refractory sandstone, shale and brick and an onshore supply of sea coal is attributed to marine reworking. A variable proportion of sand composes the beach. The sand varies in colour from an orange brown to coarse dark sand according to the proportions of local sandstone, shale rock fragments, broken shells, brick and colliery spoil. The physical description illustrates that there is an unusual range of particle sizes and a diverse composition, thus providing an ideal setting in which to investigate the sediment transport on a mixed beach.

2:2

THE TIDAL CLIMATE OF THE RESEARCH AREA

The nearest Tide level gauge to East Wemyss is at Leith. Therefore, adjustments in the Admiralty Tide Tables are required as the high water levels at East Wemyss are 0.09 metres below those at Leith (HR Wallingford 1994). The tides along the South Fife coastline are dominated by the tidal systems of the North North sea which relate to the Bergen amphidromic point. The tidal ranges for the mean Neap and mean Spring tides are approximately 2.4 and 4.8 metres respectively, therefore the coastline is classified as macrotidal.

The tidal system of the outer Firth of Forth is associated with an essentially anti clockwise circulation. The shape of estuary concentrates the flows of water in an out. Flood dominant currents flow to the Southwest along the North shore and ebb dominant currents flow to the Northeast along the South shore of the Forth (Criag 1972). Carrying out current measurements was beyond the scope of the present study however, reports are available from previous computer studies of tidal flows within the Firth of Forth. The Forth River Purification Board(1988) deployed a current meter off West Wemyss at the 9 metre contour (333340E 694470N). During the flood phase of Spring tides the currents flow Southwest parallel to the Fife shore reaching speeds of 30 cm/s (figure 2:21/2:22). After high water the ebb flows with peak speeds of 40 cm/s towards the Northeast and out of the Firth of Forth. The Neap tidal currents were less powerful with flows of 15 cm/s and 25 cm/s for the flood and ebb respectively. On their own these tidal currents will not produce any substantial net movement of beach material, as there is a reversal in the flow direction. However, a combination of wind wave action superimposed on a weak tidal current can cause substantial transport of material. Superimposed on the tidal currents is a slow steady longshore current of 2 cm/s which flows to the Southeast (HR Wallingford report 1994).

WAVE AND WIND CLIMATE OF THE RESEARCH AREA

The wave climate of Wemyss has two components; waves generated by active wind processes within the Firth of Forth and swell waves entering the Firth of Forth, after generation in the North sea. Those waves generated within the Firth of Forth approach from between 180 and 250 degrees with respect to true north. Waves generated in the North Sea approach from 50 to 120 degrees. These two contrasting waves can become superimposed to give a complex wave pattern (figure 2:23).

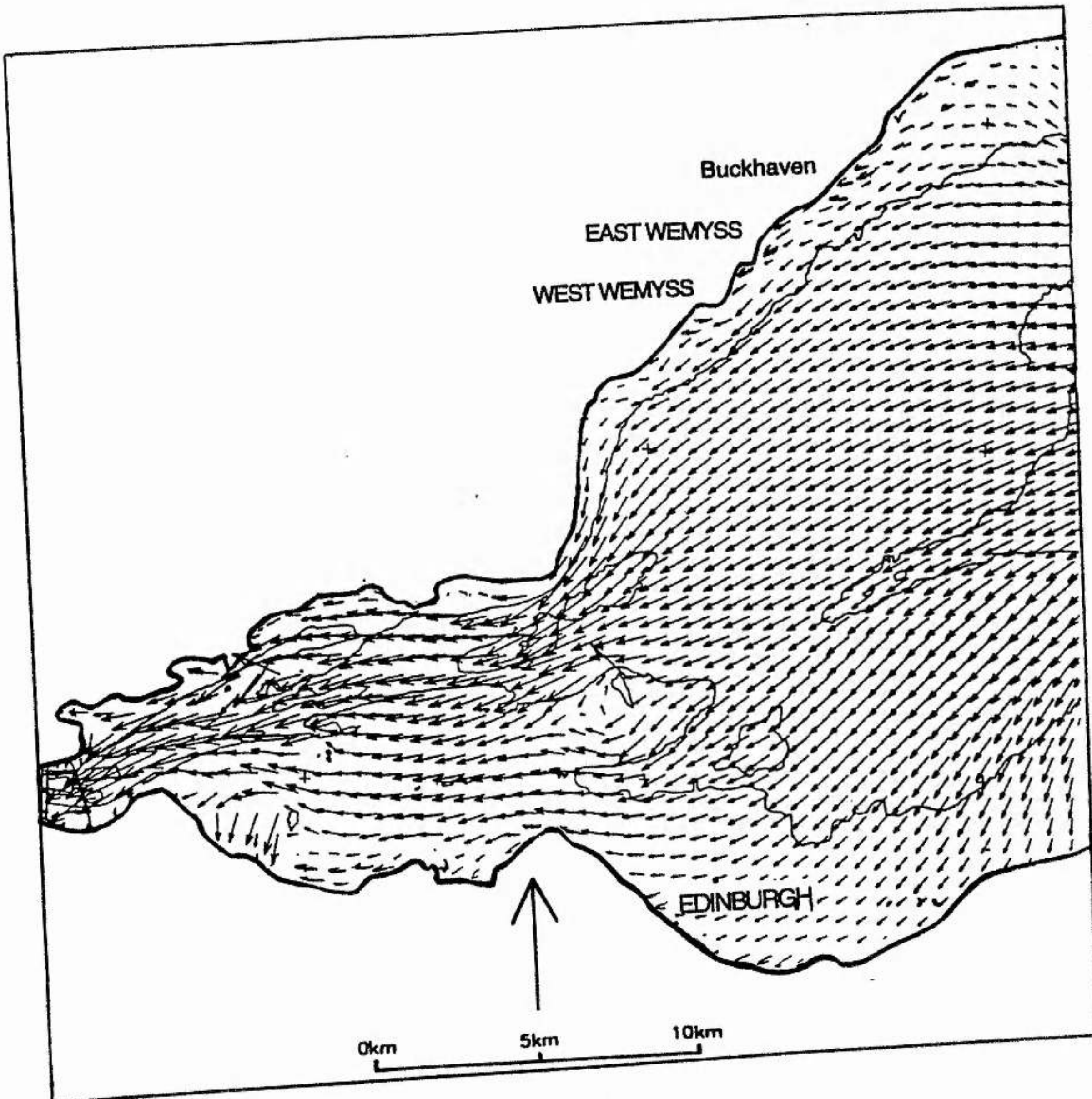


Fig 2:21 Flood phase tidal flow pattern
(modified HR Wallingford 1994).

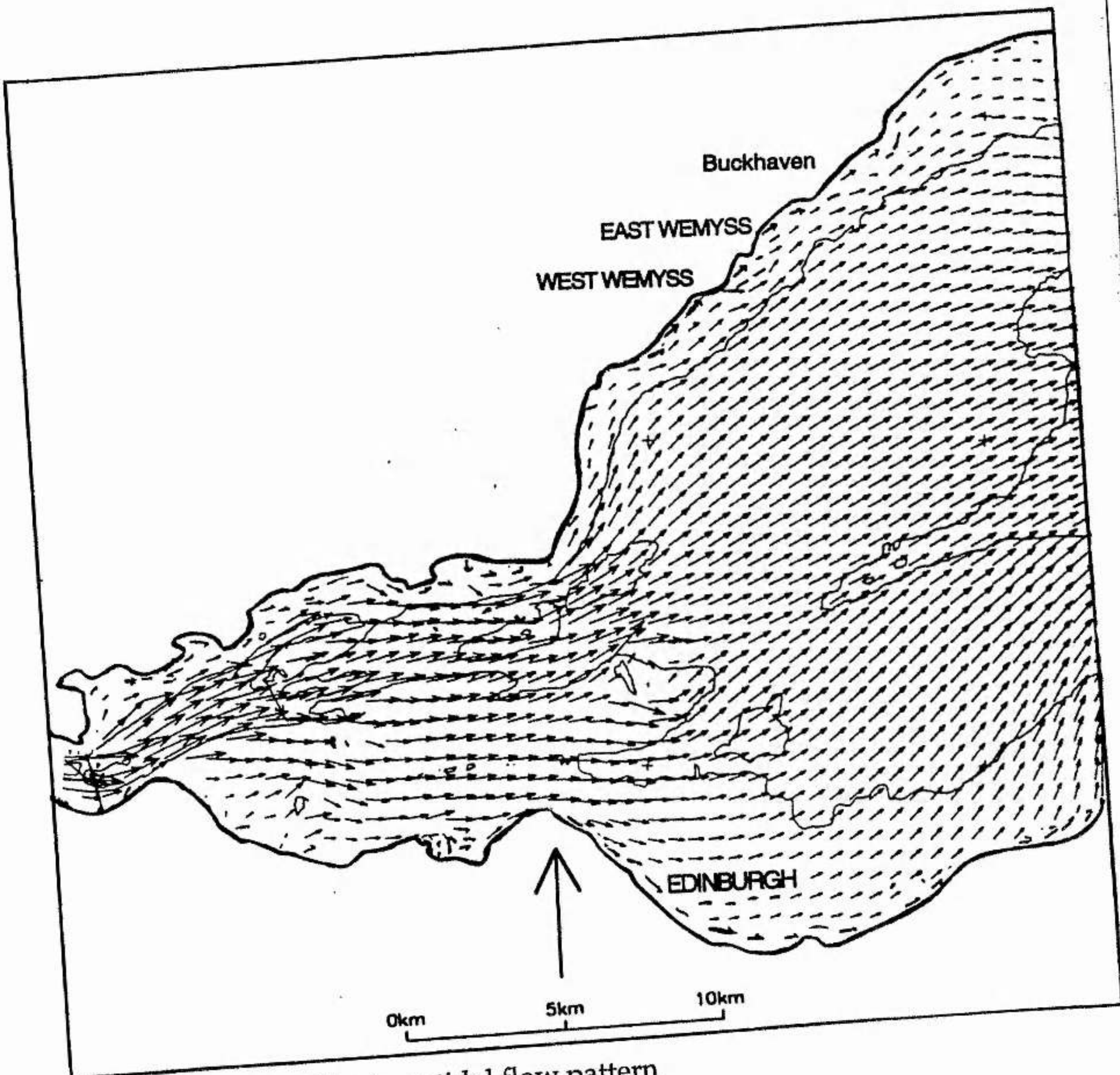


Fig 2:22 Ebb phase tidal flow pattern
(modified HR Wallingford 1994).

The local wind rose data indicates a bimodal pattern the most frequent winds are from the Southwest and a second peak is from the Eastern sector. The prevailing winds in the area are from the West and Southwest and account for account for 43% of the annual winds in the area. Wind waves generated locally within the estuary are variable in height and frequency. There is topographic control on the winds with sheltering effects from the headlands and the fetch is limited, therefore the maximum wave heights are 1.5-2 metres. The winds from the South blow for less than 2% of the year and have still smaller fetches and the waves heights generated are less than 0.5 metres. Easterly winds generated within the North North sea account for 24% of the annual winds (McManus 1990). The fetch can be up to 400 km according to the exposure and length of sea over which the waves propagate. These winds are referred to as the dominant winds, because although they are less frequent, they are energetically more significant and give rise to considerable wave heights. Furthermore, these waves are refracted and dissipate a high proportion of wave power alongshore (figure 2:24).

There is a seasonal pattern of winds, during the winter Westerly winds dominate the flow towards the East, with occasional Northeast flows. In summer Northeasterly and Easterly flows are more important, with sea breezes increasing during the day.

In conclusion, the dominant wave energy expenditure and sediment transport is to the Southwest. However, pebbles originating in the Northeast will not follow an uninterrupted path to the Southwest, as the locally wind generated waves rework pebbles to the Northeast. This research examines the resultant sediment transport patterns associated with waves from the different sectors.

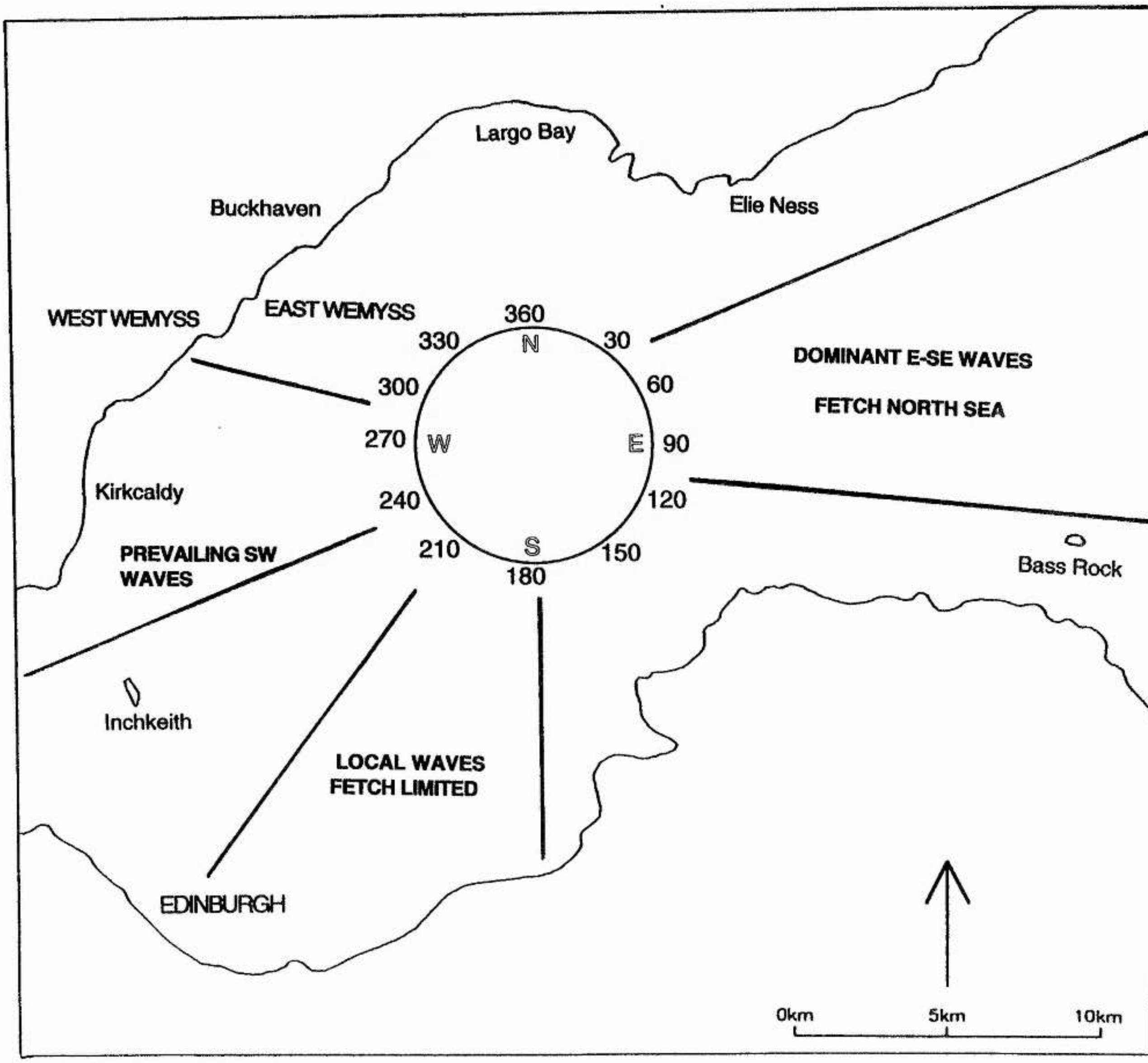


Fig 2:23 Variations in wind directions and fetch lengths.

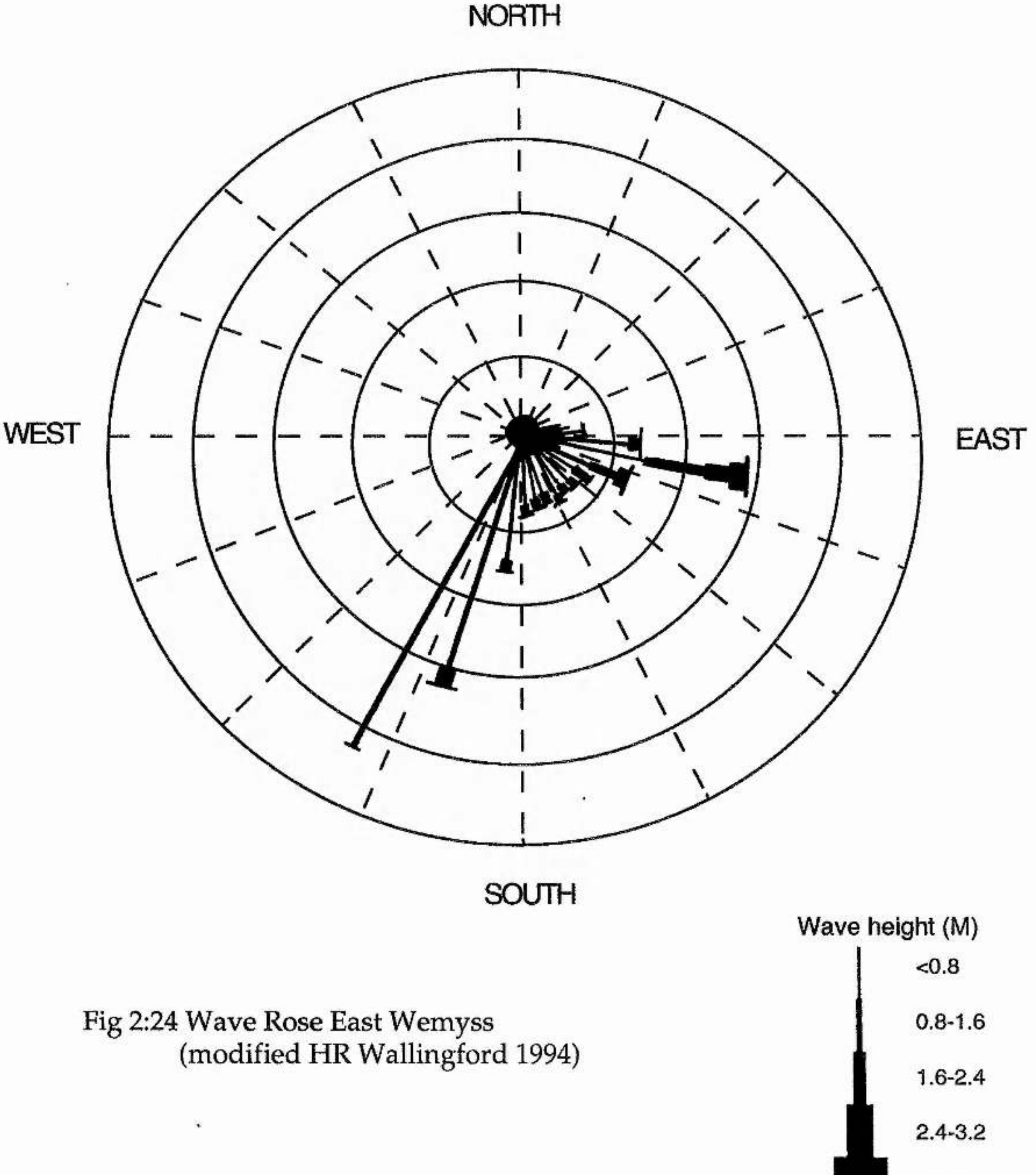


Fig 2:24 Wave Rose East Wemyss
(modified HR Wallingford 1994)

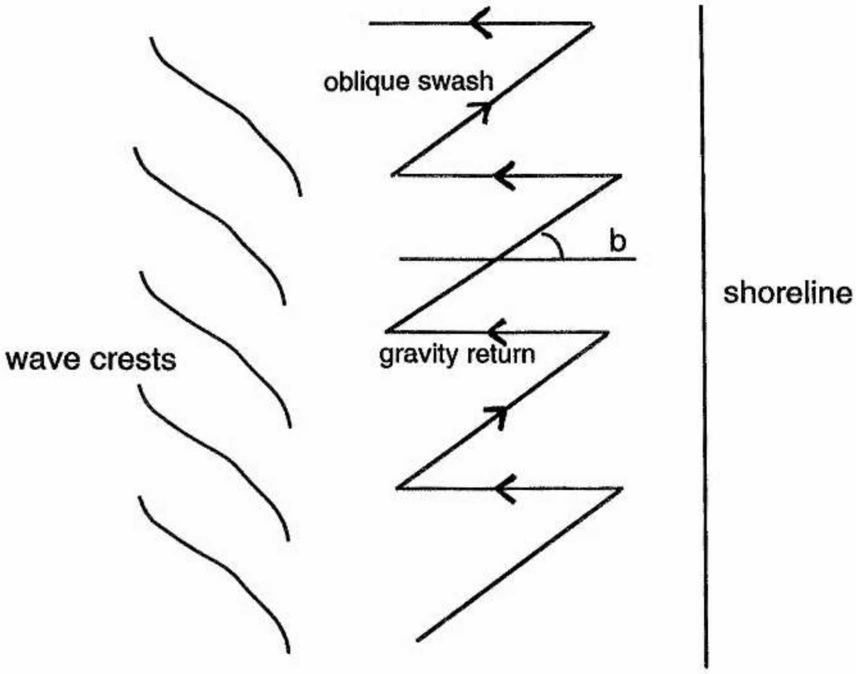
3:1 LITERATURE REVIEW

There are very few published accounts of studies examining mixed sand and pebble beaches, however there is an extensive literature on sediment transport processes on uniform sand and pebble beaches which provides a basis on which to begin investigating the response of pebbles in wave action on a mixed beach. A brief review of some of the literature is given below and further sections expand on the most important physical principles of sediment transport.

Bluck (1967) pioneered the research on the response of pebbles in wave action by examining the distribution of pebbles on shingle beaches. He showed that pebbles on beaches are organised into distinct cross shore zones, sorted according to size and shape. This sorting was attributed to the role of form on the hydrodynamic behaviour of pebbles in wave action. Following Bluck (1967), 'Selective wave transport' became the popular hypothesis to account for the distribution of pebble size and shape on beaches (Orford 1975, Williams and Caldwell 1988). A distinction was made between the behaviour of disc shaped pebbles which were carried to the top of the beach in suspension and the sphere shaped pebbles which were suspended with greater difficulty and rolled downslope, accumulating at low water. On wave retreat disc shaped pebbles were stranded, as their shape prevented them from rolling down slope. As a result of these findings emphasis was put on the longshore transport of the pebbles.

The onshore-offshore and longshore transport of sediment by the energy of the waves is unique to the beach environment. When waves approach oblique to the shoreline there is a more or less zig zag pathway of transport, associated with the swash and the backwash. As the forward movement of water particles is not entirely compensated for by a backward motion, the sediment movement is transported in the direction of the travelling waves (figure 3:1). The direction of longshore transport is determined by the strength, duration, direction of the wind and the fetch corresponding to the wind direction. The fundamental wave dynamic processes responsible for sediment transport are outlined in more detail in section 4:1.

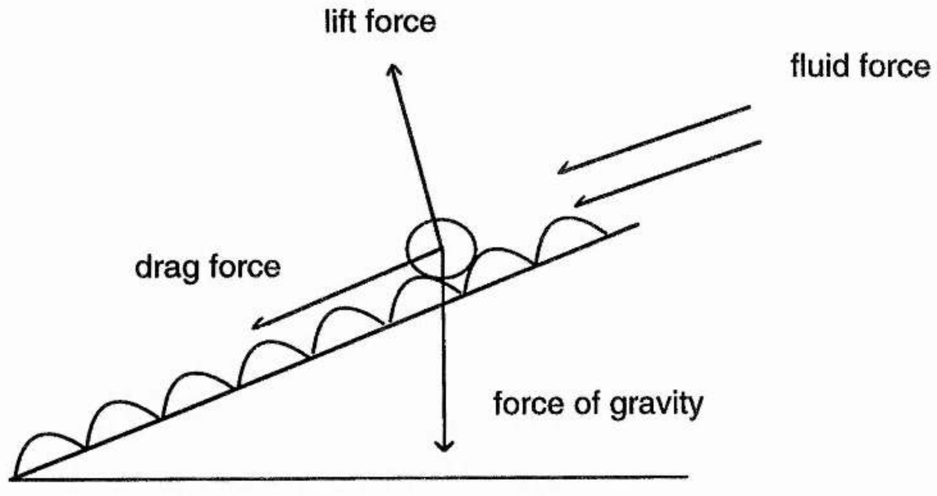
It is because of the complexity of the wave dynamics on beaches that sediment transport is still not fully understood. Numerous short term active studies have been undertaken to try and interpret the action of waves, tides, on the longshore transport of pebbles. The two most common methods of analysing transport rates and pathways, include traps (Chadwick 1987) and tracing techniques (Bray 1995, Nicholls and Wright 1991). Tracers have the advantage over sediment traps, in that they do not interfere with wave processes. A review of tracer techniques is made in section 4.3.



Longshore transport

The incoming wave swash drives the pebbles up the beach at an oblique angle and the return gravity flow washes them back to their original level.

Fig 3:1 Longshore sediment transport.



Forces acting on a pebble resting on a sloping beach face

Fig 3:2 'Excess shear stress' for sediment entrainment Bagnold (1963).

A wide selection of literature is available on sediment transport on coarse homogenous pebble beaches, Kidson et al (1959), Nicholls and Wright (1991) Carr (1971) and Caldwell (1981). Many factors influenced pebble transport which had previously not been recognised on sand beaches. Protrusion of pebbles of different shapes and sizes, and the permeability of the pebble foreshore influenced the local boundary stress conditions for the initiation of pebble transport. In consequence, pebble transport rates were found to be highly variable even on adjacent beaches. The entrainment of pebbles is discussed in more detail in section 4:2. Carr (1971) on Chesil beach (England) highlighted that once pebbles were in motion, the individual pebbles seek out sub-populations with similar pebble form characteristics, through a process of pebble rejection and acceptance. Those pebbles which were rejected from the beach framework were preferentially transported to extreme distances alongshore. The complexity of factors influencing pebble motion ensured that the transport of pebbles overwhelmed any simple transport model that had been produced for sand.

As research progressed it was evident that transport studies investigated beaches only as two dimensional features. To assess the volumetric transport rate a three dimensional assessment of beaches was required. Consequently, experimental techniques were designed to examine the thickness of the moving layer of sediment undergoing longshore transport. Bray (1996) inserted vertical pebble cores of known length into the beach face and monitored the changes in the cores after the beach face was disturbed by wave action. The depth to which the beach was disturbed was assumed to represent the maximum thickness of the mobile layer undergoing longshore transport. A more detailed review of the disturbance on beaches is made in section 7:1.

From the review of the literature it became apparent that only a small number of investigations have been made on heterogeneous beaches composed of mixed pebbles and sand (McLean 1970, Kirk 1980 and Petrov 1989). On mixed beaches the change from pebbles to a sandy foreshore is often abrupt and variable in level from time to time, according to the wave conditions. Mixed beaches investigated by Kirk (1980) were described as 'morphologically distinct and dynamically complex' in contrast to homogenous sand or shingle beaches. Therefore, the complex dynamics are not widely known and the literature is particularly small. Nordstrom and Jackson (1993) examined the distribution and transport of pebbles on a sandy tidal estuarine beach. The research highlighted that a dynamic equilibrium existed between the sediments and wave parameters that resulted in the redistribution of pebbles and sand. Preferential entrainment and transport of sand occurred in low wave energy conditions and the pebbles were buried. Whereas, in high wave energy conditions the sand was removed to leave a pebble lag. The findings suggested that 'selective wave transport' was an important phenomenon on beaches with mixed sediment sizes. Mixed beaches have a wider spectrum of pebble sizes and a more complex wave regime in comparison to an estuarine environment. Petrov (1989) similarly proposed that an important wave sediment system was established on beaches composed of heterogeneous material. Mechanical differentiation accounted for the removal of sands that resulted in an active layer of more homogenous material then the initial deposit. The sand is transported alongshore or moves into a lower less mobile beach layer, whereas an upper beach layer of coarse pebbles moves longshore and cross shore. This research attempts to enhance the understanding of the response of pebbles and sand on a mixed beach.

Today the general approach to investigate pebble transport is to apply empirical formulae which correlate the longshore wave energy to the rate of longshore transport. The formulae have varying degrees of complexity, however the general structure and principles behind the formulae are similar, with the sediment transport rate being related to the excess shear stresses applied to the sediment on the bed. In the nearshore zone there is the interdependence of numerous wave and sediment parameters. To simplify the calculation of sediment transport, the formulae contain coefficients derived from the collection of transport data. Certain coefficients remain as constants whilst others are dependent on the sediment characteristics of the beach in question. Bagnold (1963) pioneered the development of the sediment transport formulae on sand beaches by calculating the 'excess shear stresses' available after fluid forces acting on sediment per unit area have overcome the frictional and the gravitational forces of the beach sediment (figure 3:2);

$$W_b = U_b \quad G \tan \alpha = q \tan \alpha \qquad \text{(Equation 3:11)}$$

The available energy is multiplied by the bedload efficiency factor (Wb). G refers to the weight of the moving grains per unit area of the bed. If Ub is the mean velocity in the direction of flow, then the sediment transport q equals G multiplied by Ub. In addition, there is an opposing motion G tan which is the dynamic friction angle.

In the beach environment the waves provide the power to move and support sediment, however it is the superimposed longshore currents that produce the longshore component for net transport. The longshore current is generated by waves that approach oblique to the shoreline and a proportion of the breaking wave energy is dissipated in placing sediment in motion;

$$[(E.cn)_b \cos \alpha_b] / U_m \qquad \text{(Equation 3:12)}$$

Once the sediments are in motion they become available for longshore transport, by the longshore current V l;

$$I_l = K' . (E. Cn)_{b.} \cos \alpha_b . \frac{V1}{Um} \qquad \text{(Equation 3:13)}$$

$I l$ immersed weight transport past a given section of beach (m^3/s).

K' a dimensionless coefficient of proportionality.

Um maximum horizontal component of the wave orbital velocity just before wave breaking.

V1 average longshore current velocity measured at the mid surf position.

$(Ecn)_b \cos \alpha_b$ longshore component of breaking wave power.

α the angle of wave approach, E is the wave energy , Cn wave phase velocity.

Komar and Inman (1970) successfully correlated the immersed sediment transport rate to the wave and longshore currents;

$$I = 0.28 \ (E. Cn)_b . \cos \alpha_b . \frac{V1}{Um} \qquad \text{(Equation 3:14)}$$

From which a relationship of the sediment transport according to the longshore current was resolved; $V1 = 2.7 \ U_m$. The importance of the role of longshore currents in sediment transport was supported by Longuett-Higgins (1970).

The CERC longshore sediment transport formula (Coastal Engineering Research Center) was first established for the longshore transport of sand, then modified to calculate the longshore transport of pebbles. Today, the CERC formula is commonly used to predict pebble transport (Brampton 1993). The formula was selected for this research and is reviewed in section 5:2. An assessment will be made as to how well the CERC formula can be applied to a beach composed of pebbles of different composition with a variable proportion of sand.

The applicability of empirical formulae must be treated with caution as they oversimplify the processes in the beach system. Spatial and temporal variations in transport can be overlooked, in consequence the transport rates are over or under estimated. Furthermore, nearshore currents, the presence of tides and water circulation from rips are not taken into account. This research will highlight that observational and qualitative assessments of pebble transport are just as informative, especially on mixed beaches.

4:1 PHYSICAL PROCESSES

Waves are generated as a result of friction between the water and air carried by the wind. The wind stress distorts the water surface and transfers energy to the waves (Komar 1975). Wave energy derived from the wind is subsequently dissipated in the nearshore zone. The majority of this energy is dispersed in transporting sediment. Therefore, an understanding of wave dynamics is fundamental for an interpretation of sediment transport taking place on beaches. Two main types of waves can be distinguished;

SEA (WIND) WAVES are steep irregular waves that have been generated by winds blowing over the water surface. The size of wind generated sea waves are controlled by the wind speed, the duration of the wind and the length of open water across which the wind can blow, 'a distance referred to as the fetch'. Sea waves have a variable direction of propagation, height and frequency. The generating winds are still active, when the waves reach the shoreline.

SWELL WAVES are originally generated as sea waves by the wind in a storm centre. Swell waves propagate outward from the generation area to create regular, long period waves from the coalescing of sea waves. Unlike seawaves, the generating winds have ceased by the time swell waves reach the shoreline.

A physical description of waves includes the surface form and the water particle motion within the wave form. Important wave characteristics are described below;

WAVE LENGTH (L) is the horizontal distance between successive wave crests.

WAVE HEIGHT (H) is the vertical distance between the highest point of the wave crest and the lowest point of the wave trough.

WAVE CELERITY (C) is the velocity of wave propagation.

WAVE PERIOD(T) is the time required for one wavelength to pass a fixed point.

WAVE STEEPNESS (H/L) is the ratio of wave height to the wave length.

WAVE DYNAMICS IN DEEP WATER

In deep water Airy's (1845) linear wave theory describes simple oscillatory wave motion. The theory assumes that waves do not interact and the bed is a horizontal, fixed impermeable boundary. In deep water an oscillatory water motion is set up within the wave, which involves the rotation of water particles in circular closed orbits. These circular orbits lie in a vertical plane which is parallel to the direction of wave advance. As each wave crest passes the water surface is elevated and within each wave crest there is the simultaneous forward motion of the water particles in the direction of wave advance. After the crest has passed the water surface is lowered and as each wave trough passes the underlying water moves in a direction opposing the direction of wave advance. Therefore, there is no net directional displacement of water (figure 4:1).

In deep water, the diameter of the circular orbits decrease exponentially with depth beneath the water surface. The velocity of the orbiting water particles is determined by the orbital diameter. In deep water the water depth is large compared with the wave length, therefore at a depth of half the wave length the orbital diameters and velocities became negligible (figure 4:2). Mathematical terms are used to describe the wave motions. The celerity or velocity at which the wave form propagates is controlled by the wave length according to the following relationship;

$$C = \left(\frac{gL}{2\pi} \tanh \frac{2\pi d}{L} \right) 0.5 \qquad \text{(Equation 4:11)}$$

C wave celerity(m/s)

L deep water wave length(m)

π 3.142.....

g acceleration due to gravity (9.8 m /sec^2)

tan h hyperbolic tangent

d water depth (m)

In practice it is comparatively easy to measure the wave period and depth, however not the wave length. In deep water when d/L is large then tan h (2 π d/L) approaches unity, therefore the equation above can be simplified;

$$C = \left(\frac{gL}{2\pi} \right) 0.5 \qquad \text{(Equation 4:11b)}$$

As the distance travelled by a wave in one wave period is equal to one wavelength, the celerity is therefore related to the wave period and wave length (T = L/C) The speed of water particles within each wave is given by the following relationship;

$$U = \frac{\pi H}{T} \qquad \text{(Equation 4:12)}$$

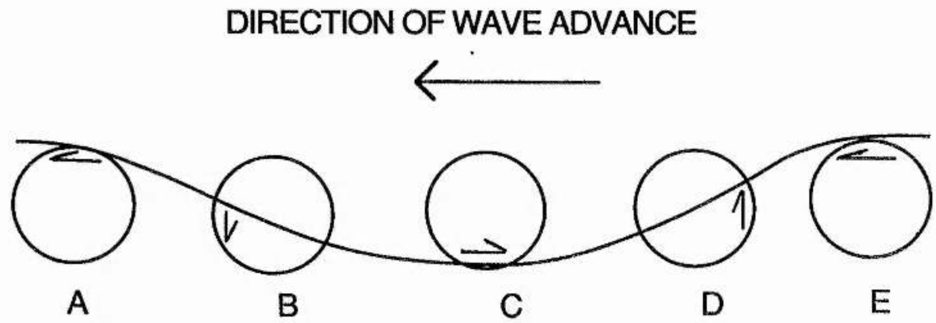
U speed of water particles(m/sec)

H wave height (m)

T wave period (s)

π 3.142....

In deep water small increases in wave period (T) result in large increases in wave length (L). This results in the long period waves travelling at a faster velocity than short period waves. Consequently, long period waves disperse more energy in the nearshore environment in comparison to the short period waves which move more slowly.



Sketch Profile, in vertical plane parallel to the direction of wave propagation, symmetrical wave oscillation motion in deep water

Fig 4:1 Wave propagation in deep water.

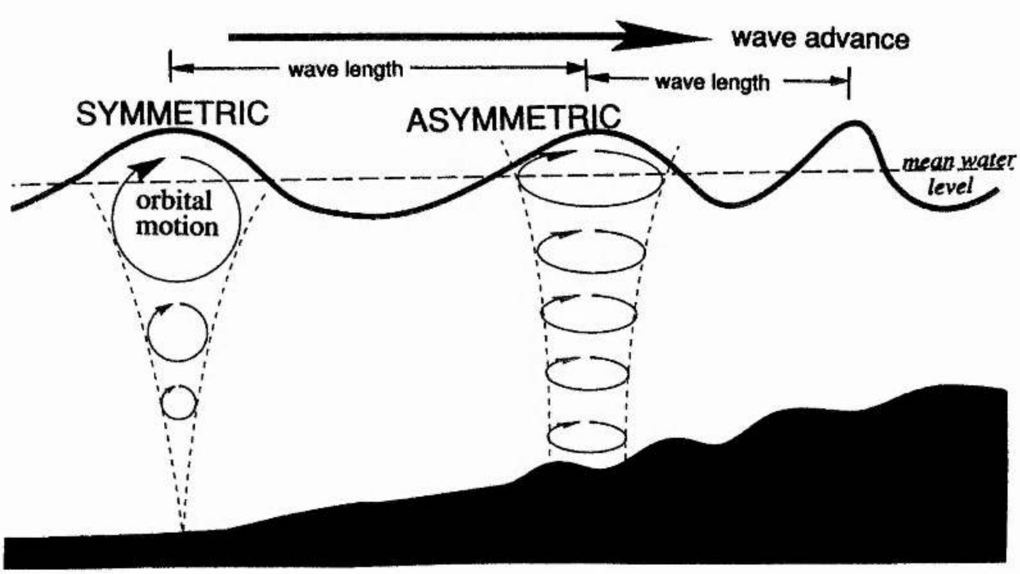


Fig 4:2 Wave motions in deep water and shallow water
(modified Komar P.D Beach Processes and sediments 1976).

WAVES IN SHALLOW WATER

As waves enter marginal shallow waters the water depth is 1/20 of the wave length. The water motion and wave form undergo various changes referred to as 'shoaling transformations'. In shallow water the circular orbits change to ellipses. The long axis of the ellipses are parallel to the sea bed. As the elliptical pathways do not vary significantly with depth the horizontal velocities of the elliptical orbits remain the same. The ellipse orbits are no longer closed and water particles are projected forward in the direction of wave advance. The ellipse is converted into an onshore-offshore water motion which is capable of generating bedload transport. Under the wave crest there is a rapid shoreward motion, whereas the seaward flow under the troughs is less significant (figure 4:2).

The celerity or velocity of a wave proceeding shoreward decreases as the depth of water in which the wave is travelling becomes shallower. The celerity is proportional to the square root of the wave depth in shallow water. The wave length also decreases with depth, however the wave period remains constant;

$$C = \frac{L}{T} = C\sqrt{gd} \qquad \text{(Equation 4:13)}$$

The term tan h (2πd/L) becomes equal to 2πd/L, thus the hyperbolic tangent can be dispensed with. The velocity of the water is given below;

$$U = \frac{\pi H}{T \sin h\ 2\pi\ d\ /\ L} \qquad \text{(Equation 4:14)}$$

U velocity of water translated in the direction of propagation (m/s)
H wave height (m)
π 3.142.......
T wave period (s)
Sin h hyperbolic sin
d wave depth (m)
L wavelength (m)

WAVE REFRACTION

In shallow water the waves react with the bottom topography. The wave length and velocity alter as the waves progress shoreward, however the wave period remains constant. The part of the wave crest in deep water is moving faster than the rest of the wave in shallow water, in consequence the wave crest lines become aligned with the bottom contours and bend to become parallel with the shoreline. This crest alignment is referred to as wave refraction. Rays or orthogonals are plotted at right angles to the wave crests. The convergence of the orthogonals concentrates the wave energy in a smaller area and the wave heights increase. Conversely, diverging orthogonals reduce the wave energy and height. A coastline with irregular bathymetry will cause the waves to be refracted in a complex way producing variations in wave height and energy alongshore (figure 4:3).

WAVE BREAKING

During shoaling transformations the wave height progressively increases until a critical point is reached and the wave breaks. When the wave crest velocity exceeds the decrease in the wave phase velocity, the crest is left unsupported, at an angle of approximately 120 degrees and collapses. The maximum water particle velocity occurs under the breaking waves and leads to a mass transport of water shoreward. This should occur at H/hb=1 (b is the subscript of breaking height), however observations indicate the ratio can vary between 0.73 and 1.03. The most widely used ratio is 0.78 (McCowan 1984).

Galvin (1972) classified 4 types of wave breaker; (figure 4:4)

A spilling breaker gradually peaks, the crest then becomes unstable and foaming water is observed as the crest of the wave moves forward faster than the wave as a whole.

A plunging breaker has a shoreward crest that steepens and becomes vertical. The wave crest curls over then plunges down as an intact mass of water and entraps air.

A collapsing breaker is intermediate between the plunging and surging types.

A surging breaker peaks as if to plunge but the base of the wave then surges up the beach face and the crest collapses.

This sequence of wave breakers was correlated to an increase in the beach slope and a decrease in the wave steepness ratio H/L. The beach slope controls the time or distance spent by the wave in moving through shallow water towards breaking. The greater the time or distance spent on the beach slope increases friction and changes the wave shape.

On breaking waves are transformed into swash, the swash consists of a thin sheet of water that does not percolate into the beach face and flows up the beach slope against friction and gravity. The swash velocity gradually decreases up the foreshore, the water then stops and begins to flow down the foreshore slope as backwash. As the backwash flows down the beach face it gains speed under gravity as it overcomes friction. The backwash velocity is influenced by the beach face slope, grain size properties and the permeability of the beach face (Caldwell and Williams 1985). The interaction between the breaking wave and the returning backwash of the preceding wave is referred to as the phase difference (Tb/t) (Kemp 1963). If the swash period (t) approaches the breaker period (Tb) collision results. On steep shingle beaches the backwash from a

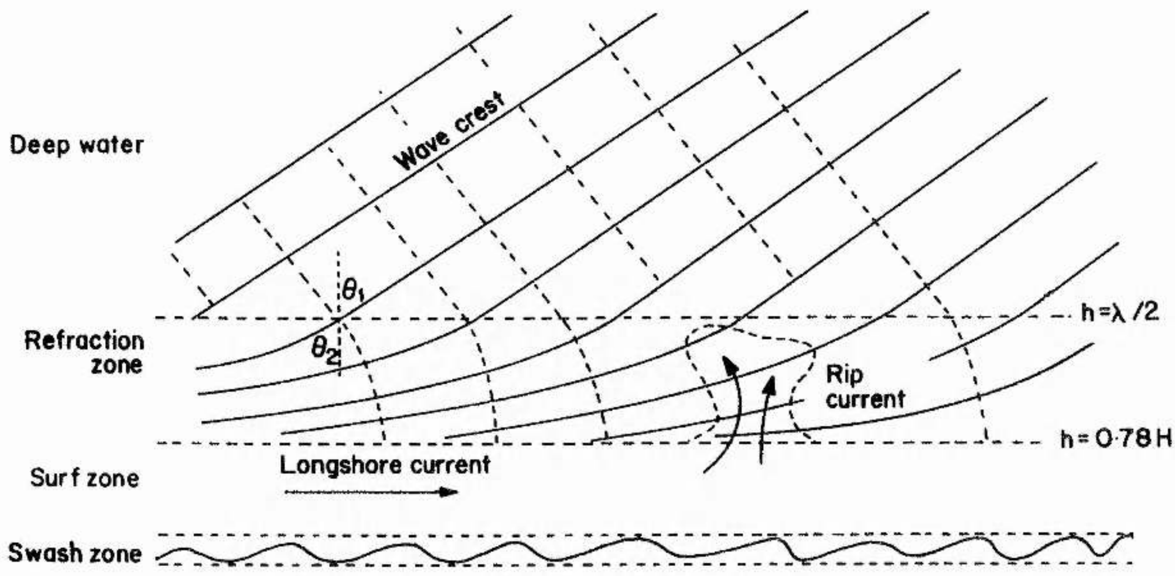


Fig 4:3 Shallow water (h= λ /2)Wave refraction to wave breaking (h=0.78H) (source Dyer K.R. 1986).

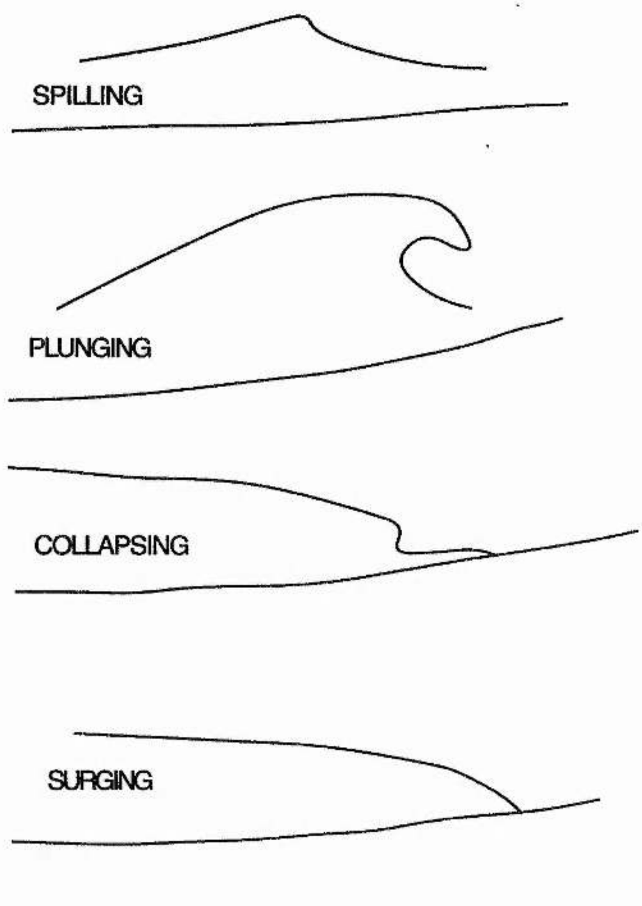


Fig 4:4 Wave breaker classification (Galvin 1972).

breaker wave has a high velocity and commonly interacts with the subsequent breaking wave (Miller and Zeigler 1980).

WAVE INDUCED CURRENTS

It is the wave energy that mobilises sediment. However, it is wave induced currents that transport sediments in the longshore direction (figure 3:1). Shore normal currents are produced by the onshore-offshore movement of water particles within the waves. Waves that approach at an oblique angle to the shore create longshore currents which flow parallel to the shore. These wave induced longshore currents are often interrupted by seaward flowing rip currents. The direction of the longshore currents are related to the direction and angle of wave approach. The beach configuration adjusts so that the intensity of the longshore currents is minimised, when a headland projects from one end of the beach, a log spiral or zeta curve bay of refracted wave crests is formed.

Bowen and Inman (1969) and Longuet-Higgins (1970) demonstrated that the variations in wave breaker height alongshore as a result of refraction and bathymetry effects produce variations in the wave set up. The wave set up causes a local rise in the water level above the still water level as a result of variations in the velocities and pressures beneath the waves. These variations in the wave breaker height generate a driving force for the development of the longshore currents. This driving force is expressed in terms of a gradient of wave momentum flux or 'radiation stress'. Consequently, the pressure gradient drives the longshore currents from positions of high to low waves.

Furthermore, when reflected wave energy is trapped inshore by refraction and when wave breakers interact 'secondary waves' are created. These secondary waves are at right angles to incoming incident waves and are referred to as 'infra gravity waves'. Infragravity waves, include edge waves that remain stationary and rise up and down trapping wave energy inshore. These edge waves are superimposed on the incident waves and extract their energy from them. Although these secondary waves cannot be observed, research has highlighted that these waves are important for sediment transport as they generate local variations in turbulence and complex water motions (Wright, Guzza, Short 1982).

TIDAL CURRENTS

Tides are significant to sediment transport as they result in a systematic rise and fall of sea level which causes the active wave zone to migrate across the beach profile. It is the moons orbit around the earth which is primarily responsible for oceanic tides. The earth and the sun are further apart, therefore the tide producing effect of the sun is less powerful than the moon.

LUNAR TIDES

As the Moon moves in its orbit, the barycentre (or centre of mass) of the earth makes a complementary movement in opposition. As the moons position changes with respect to the earth, the gravitational force distorts the sea surface. If the sea surface is considered as a prolate water spheroid, then each end of the spheroid would represent a tidal bulge. The long axis of the tidal bulge is controlled by the position of the moon as it moves around the earth, approximately every 28 days. The rise and fall of the water depends on the position of a point on the earth, with respect to the long axis of the water bulge. Each high tide occurs about 12 hours and 25 minutes after the preceding tide. Therefore, the lunar tides are 51 minutes later each day.

As the positions of the sun and moon change with respect to the earth's equator, tides fluctuate in a systematic way. When the forces of the moon and sun are acting in a straight line drawn through the earth the tide rising force is at a maximum, because the tidal bulges of the moon and the sun combine. This situation occurs at the new and full moon, these maximum tides are referred to as Spring tides. There is a time lag of 1.5 days for the maximum tides after the full or new moon positions. When the moon and sun are at a 90 degree angle with respect to each other then the tidal bulge is out of phase and a minimum tidal range is produced. These tides are referred to as Neap tides. The sequence of Spring tides through to Neaps and back again takes one lunar month which is approximately 29 days (figure 4:5).

ADDITIONAL FORCES ON TIDES

The rotation of the earth produces a geostrophic force referred to as the 'Coriolis force'. In the northern hemisphere the Coriolis force veers to the right. Consequently, the tidal wave oscillates around the nodal 'amphidromic point' in a counter clockwise direction in the North North sea. The tides are also affected by the angle of the sun. At the equinoxes the sun is overhead at the equator this produces a maximum tide rising force and results in an additional range to the Spring tides around the 21 September and the 21 March. Conversely, at the solstices the sun is high and the earth-moon-sun line is not straight, therefore the lowest Spring tides occur around 21 June and the 21 December. The tides also show seasonal variations. In the North hemisphere, in winter the earth moves closer to the sun therfore, the tides are higher than the summer tides.

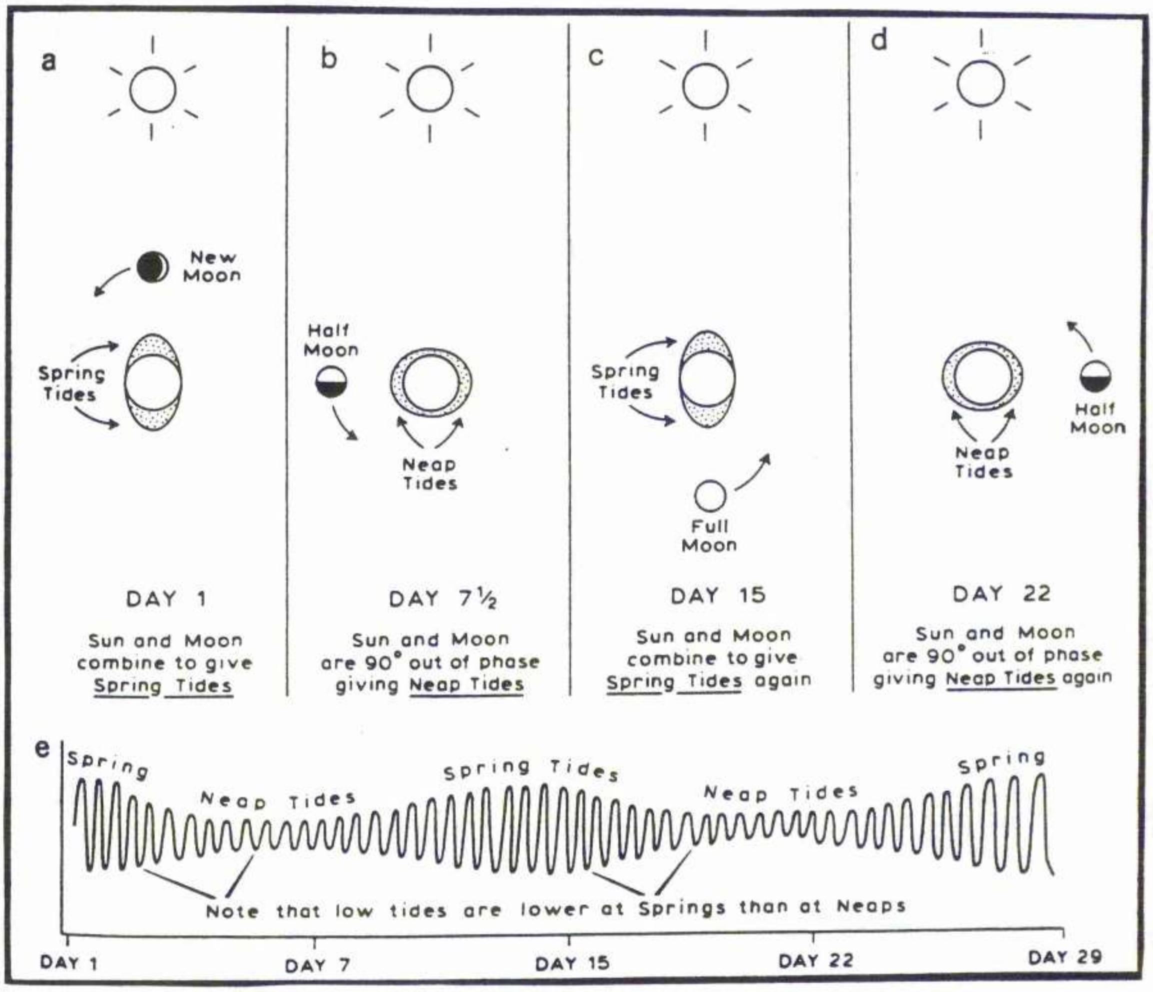


Fig 4:5 Tidal sequence Springs to Neaps (source Pethick, J. 1984).

Furthermore, the level attained by predicted tides can be greatly altered by the prevailing climatic conditions. Changes in barometric pressure can influence the tide level. 'Normality' is calculated as 990mb pressure, and the tidal water levels are calculated for this condition. However, a drop of 10mb in pressure can produce a 0.1metre rise in the sea surface. When a significant cyclonic low is coincident with onshore gales the sea surface will be greatly elevated.

It is clear from this brief review that the mechanisms of wave motion are far from simple and the energy dissipation associated with wave breaking in the nearshore is complex. On their own tidal currents are not very significant in generating sediment transport however when superimposed on wave action substantial transport can result. This research examines the relationships between the wave parameters and the sediment dynamics. The following section outlines how the water flow in shallow water initiates sediment transport.

4:2 THE INITIATION OF SEDIMENT TRANSPORT IN THE NEARSHORE ZONE

The review of wave dynamics indicated that in marginal waters, the water flow reacts with the solid boundary of the bed. Contact with the bed exerts shear stress that generates resistance to flow. The effects of the shear stress are transmitted upwards and a velocity curve is created in the water column above. The structure of this velocity curve is referred to as the 'Boundary Layer'. The water in immediate contact with the solid boundary of the bed adheres to it and is stationary relative to the surface even when the remainder of the water is flowing. This layer is referred to as the viscous sublayer and is a few millimetres thick. Above is a transitional layer or a 'buffer layer' to the overlying fully turbulent layer, in which the velocity increases logarithmically with height to a maximum at a certain distance above the bed. Thereafter, the velocity increases more slowly as it reaches that of the freely flowing water.

In the nearshore environment the boundary layer is rough turbulent, because bed particles commonly project through the viscous sublayer. The breaking waves induce local turbulence and secondary movements of water particles in small eddies are superimposed upon the primary translation of the water. In this situation the turbulent eddies influence the boundary layer to the bed, therefore the sublayer and transitional zone are absent and the water flow does not necessarily reach the velocity of the freely flowing water (figure 4:21). For the purpose of predicting sediment motion the structure of this boundary layer is of prime importance.

For sediment transport to occur the flow conditions at the bed must exceed a minimum or threshold velocity. Shields (1936) pioneered the research into sediment thresholds by examining the relationship between the critical bed shear stress T_c (or critical friction velocity U*) required to move a uniform sediment on a smooth plane bed under unidirectional flow. The Shields parameter which has a dimensionless value combined the various flow and sediment parameters. In the equation ps and pf (kg/m^3) are the sediment and fluid densities respectively, g (m /s) is the acceleration due to gravity, D (m) is the grain diameter. The critical bed shear stress is equal to $T_c = p \quad U*$, Where U* is the critical friction velocity (threshold), when the water flow exceeds the critical value, sediment movement is initiated;

$$\psi \frac{\tau_c}{(\rho_s - \rho_f)gD}$$

(Equation 4:21)

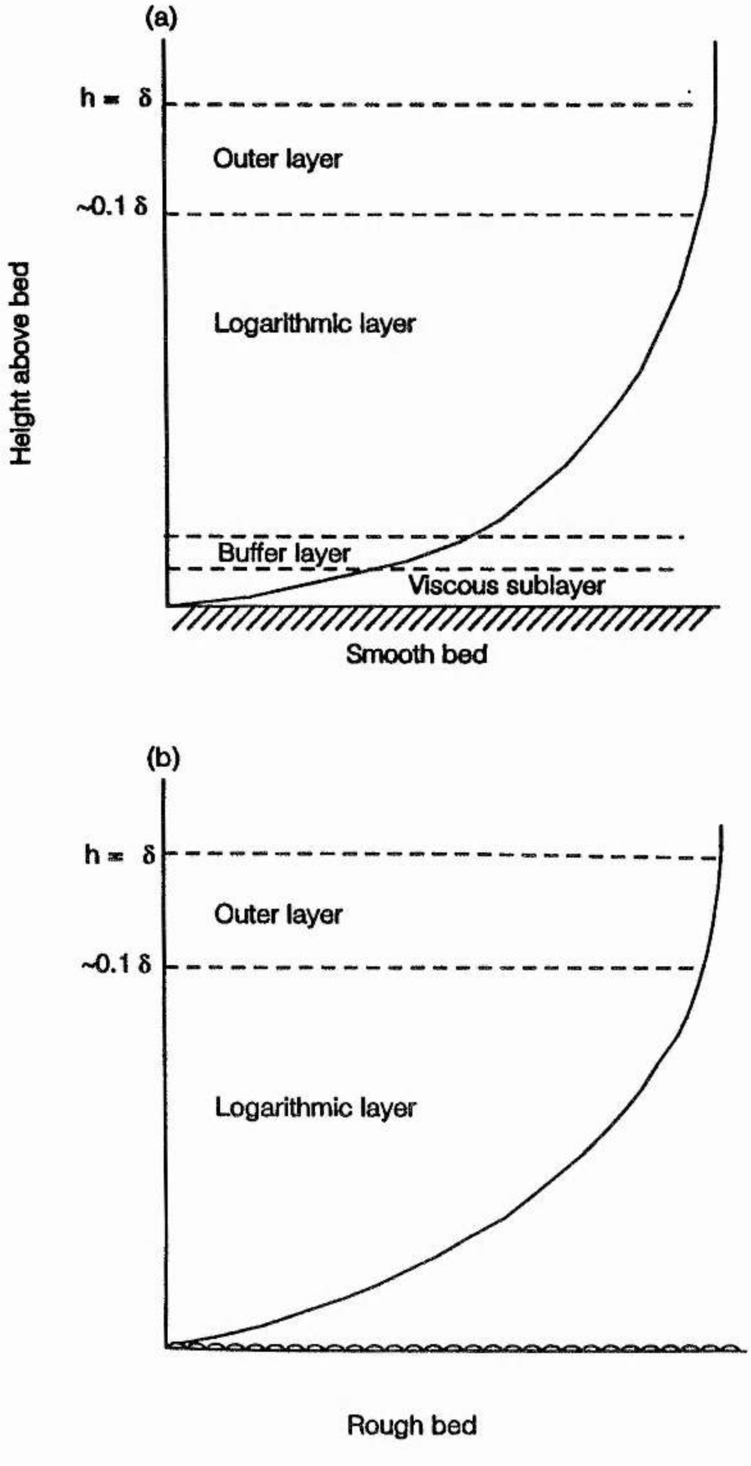


Fig 4:21 Boundary Layer structure (a) smooth turbulent flow
(b) rough turbulent flow
(modified source Dyer, K.R. 1986).

Shields produced a 'threshold diagram' referred to as the Shields curve to relate the sediment grain size to the critical flow velocity (figure 4:22). The Reynold's number compares the relative importance of inertial and viscous forces that determine the resistance to flow.

$$Re = \frac{p \; U^* \; d}{\mu} \qquad \text{(Equation 4:22)}$$

p fluid density (kg/m^3)

U* mean shear velocity(or critical boundary shear stress

d flow depth (m)

μ fluid kinematic viscosity (μ / p) μ - molecular viscosity of the fluid

It is at high values of Re* that pebble movement takes place (>10^3), where the Shields curve attains a constant value at approximately 0.045. Thereafter, the threshold value for pebble transport becomes independent of Re* and the Shields parameter. Pebble transport thresholds were investigated by Evans and Hardisty (1989), Hammond (1984) and Heathershaw (1989). The critical threshold velocity required for the transport of pebbles was found to be significantly lower than that predicted by the Shields curve (1936) and pebble thresholds displayed a distinct lack of consistency. Komar and Miller (1970) compared the entrainment of coarse pebbles and sands under oscillatory flow and established that the protrusion of pebbles of different sizes and shapes increased the roughness and local turbulence of the boundary layer (Morfett 1992). Consequently, the pressure difference vertically across a pebble created 'lift and drag forces' for the initiation of pebble transport (Isla 1993). Therefore, the Shields curve is only applicable to a smooth plane bed with touching particles that do not protrude far into the boundary layer structure.

Once pebble transport has been initiated there are various modes of longshore transport. Suspension occurs when the vertical component of the turbulent wave velocity is approximately equal to the settling velocity of the pebble. Pebbles which are transported close to the bed are collectively known as bedload. Rolling and sliding occur when the shear stress is close to the sediment threshold values and the exposed pebbles are forced to roll out of their positions. Saltation is initiated by impulses of fluid drag and lift, that cause pebbles to jump into the flow at an angle, with a trajectory that is concave downward. If there is sufficient inertia in the pebble on landing, it may cause the scatter of other pebbles. The transport modes are distinct, however they occur together throughout a wide range of transport stages. It is the proportions of grains moving in the different modes that varies (figure 4:23).

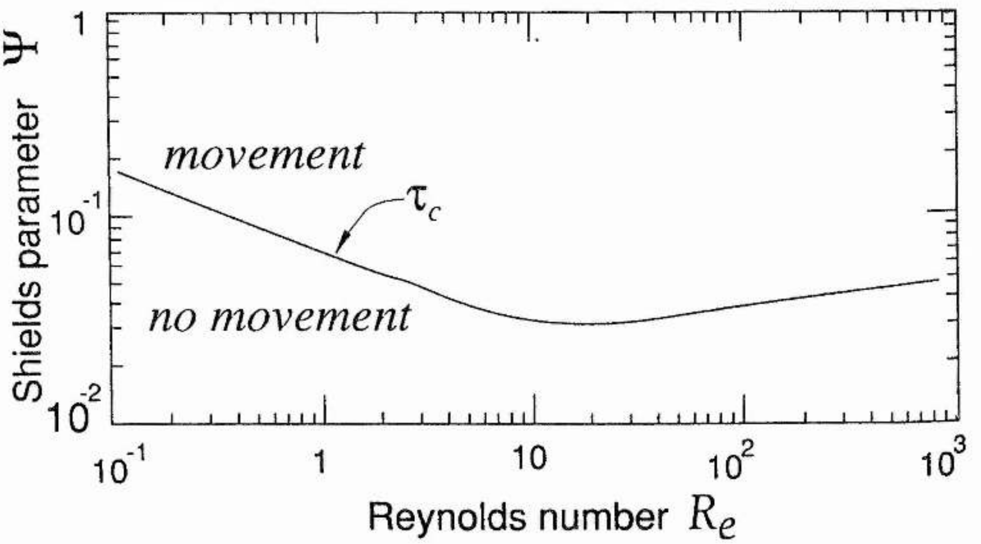


Fig 4:22 Shields curve (1936) (source Komar, P. D. 1976).

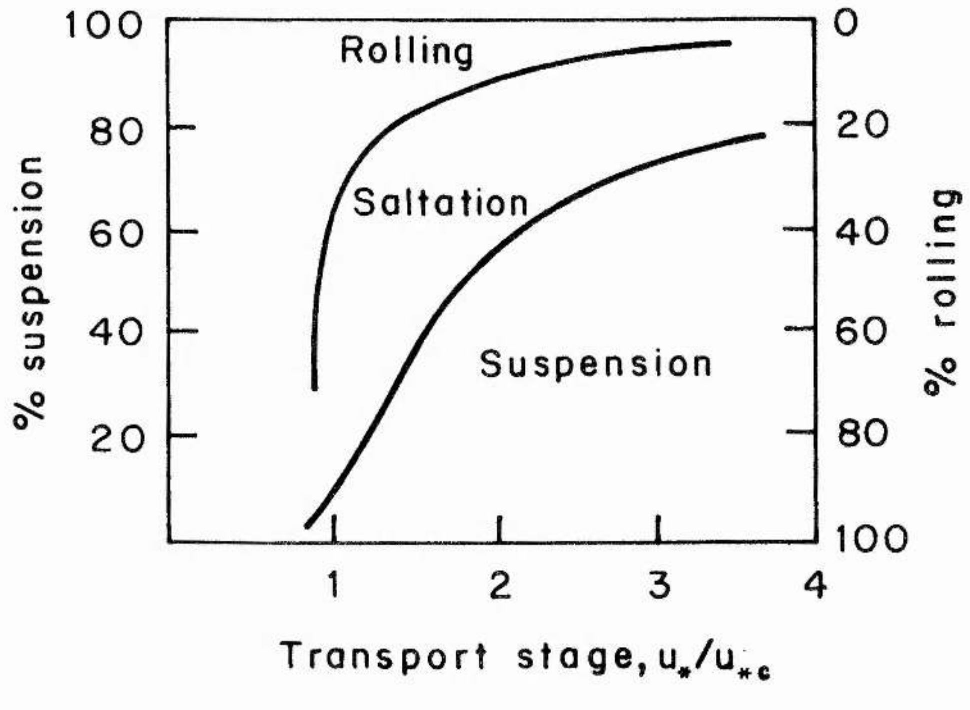


Fig 4:23 Modes of longshore transport - Threshold of friction velocity U* / U* C (source Komar P.D. 1976).

The previous section highlighted that in the nearshore environment wave breaking is superimposed on an unsteady oscillatory wave motion. Battjes and Stive (1980) attempted to model the peak energy dissipation and shear stress available for sediment transport at wave breaking, by calculating the mean energy dissipation rate per unit area over the wave length. However, this was an oversimplification, because in reality the shear stress and energy distribution are not uniform over the wave breaker. Furthermore, the collision of the breaking wave with the returning backwash of the previous wave generates impulsive forces within the turbulent boundary layer, which are not the kind of conditions to which the Shields formula can be applied (Miller and Zeigler 1980).

To date there has been little attempt to distinguish between the significance of current and wave parameters in initiating sediment transport. However, research by Thorne, Williams and Heathershaw (1989) and Voulgoris, Wilkins and Collins (1994) highlighted that the action of a wave on a current increased the bed roughness and shear stress, which consequently lowered the critical velocity required for sediment entrainment. Pebble transport within the moving sediment layer was investigated by monitoring the acoustic noise generated by collisions between the pebbles in transport. Subsequent laboratory calibration converted the acoustic noise into a sediment transport rate. In addition, to the shear and normal stresses that are responsible for pebble entrainment, the interplay of waves and currents generated instantaneous stresses which caused intermittent uprushes of high velocity flow. As a result intense pebble movement was followed by relatively quiescent periods, even when the wave conditions were steady.

This review highlights that the initiation of sediment transport is dependent on the interplay of numerous sediment and wave parameters. This research focuses on a beach with an unusual mix of pebbles of different composition and size, and a variable proportion of sand. It is therefore assumed that the threshold for pebble transport will deviate from thresholds derived on homogenous shingle beaches.

4:3 A REVIEW OF PEBBLE TRACER TECHNIQUES

The most successful method for investigating sediment transport without causing disruption to the beach system is to undertake a tracer survey. Furthermore, tracer techniques enable the actual transport behaviour of pebbles to be investigated at various points on a beach, in response to the interaction of waves, tides and longshore currents.

A tracer models the physical characteristics of the indigenous sediment in a beach system. It is assumed that once the tracers are deployed they mix evenly with the sediment in the beach system, so that following a suitable interval of time the transport behaviour of tracers will be representative of the indigenous sediments. Tracer techniques were first developed in the 1950's and 1960's to investigate sand transport on beaches. The tracing of sand provided important insights into the rates and directions of transport and so the tracing techniques were applied to shingle beaches. However, to create an appropriate tracer that models the physical form of pebbles was far more complex in comparison to sand. Consequently, the responses of pebbles on beaches are still not widely known.

REQUIREMENTS OF A TRACER

- The hydraulic properties of the tracer and the indigenous pebbles must match, if correct assumptions on pebble behaviour are to be made. The tracers must model all the physical form parameters of the indigenous pebbles i.e. the density, shape and size.
- The tracers must take into account the spectrum of pebble sizes, shapes and compositions distributed within the beach system.
- A sufficient volume of tracers must be introduced into the beach system, in order for the tracers to provide an accurate comparison to the beach sediments.
- The tracers must be clearly visible and detectable against the background of natural pebbles.
- The tracer needs to be durable, non corrosive or reactive with salts.

PEBBLE TRACER TECHNIQUES

Below is a brief review of the tracer techniques that are available, with emphasis on certain advantages and disadvantages.

FOREIGN TRACERS

Foreign pebble tracers composed of quartz granulites and basalts were deployed on Chesil Beach on the South England coast (Carr 1971). The foreign tracers were easily distinguishable from the indigenous flint and chert pebbles, as the tracers contrasted in colour. As the foreign tracers failed to model the density, shape and size of the indigenous pebbles, the foreign tracers were rejected from the mobile layer of the chert and flint pebbles and were preferentially transported to extreme distances alongshore. Therefore, caution must be taken to ensure the physical characteristics of the foreign pebbles are representative of the indigenous pebbles.

COLOURED AND MARKED TRACERS

Pebbles selected from the beach system under investigation were coated with a durable paint or the pebbles were marked in such a way that they were distinguishable from the unmarked pebbles on the beach (Kidson and Carr 1958, Gleasen 1970). Effective marking of the pebbles increased visual tracer recovery totals after deployment. However, the tracers were found to arouse public interest, which reduced the efficiency of the experiments. Furthermore, if thick coatings of paint are applied the hydrodynamic performance of the tracers are effected.

FLUORESCENT TRACERS

Pebbles selected from the beach system were coated with a fluorescent paint or dye (Jolliffe 1964 and Ingle 1973). The fluorescent tracers required detection under an ultra violet light, normally provided by a hand held lamp. A disadvantage of this technique was that tracer searches were restricted to hours of darkness, therefore site location could be problematic. However, the behaviour of the fluorescent tracers could be examined in low water, which is an advantage over other techniques.

The major drawback of the pebble tracer techniques described so far are that tracer recoveries are limited to the surface of the beach face by visual detection. If a high proportion of tracers are not recovered, incorrect assumptions about pebble transport are inferred. Tracers buried too deeply to be subject to the influence of the immediate wave attack remain undetected below the mobile sediment layer until they are re-exhumed. Subsequent relocation of these buried tracers will not reflect transport under the prevailing wave conditions and incorrect assumptions on pebble transport will be inferred.

The following tracer techniques enabled tracers to be recovered at depth below the beach face;

RADIOACTIVE TRACERS

Once pebbles had been selected from the beach environment a radioactive element was absorbed onto the pebble surface or a hole was drilled into each pebble and filled with a radioactive element, such as Barium 140 isotope which possessed a 12 day half life. The radioactive element decayed rapidly and was detectable for only a few weeks, which was considered relatively safe. Recovery of the tracers in the beach environment required a gigercounter to detect the radioactive element. Obviously, there is regard to the safety of this tracer technique and specialised staff and equipment are required. Furthermore, the method is time consuming and costly. However, tracer detection occurred to a depth of 30 cm within the beach face, which gave a crude indication of the thickness of the moving sediment layer undergoing longshore transport (Kidson, Smith and Steers 1958, Jolliffe 1964, Crickmore 1976).

MISCELLANOUS TRACERS

Magnetic pebbles have been constructed by drilling a hole into the pebble into which a magnet was placed. Subsequent recovery of the magnetic tracers involved the use of a magnetic detector. Another technique involved tagging concrete or brick with wire. Steel tags secured on pieces of brick were used to investigate transport patterns in the Bristol Channel by Kidson et al (1959).

ALUMINIUM TRACERS

This tracer technique involves the manufacture of artificial pebbles (Wright, Cross and Webber 1978). Aluminium was poured into moulds to reproduce the size, shape and density (2,700 kg/m^3) of the indigenous flint and chert pebbles. After deployment the tracers were recovered with a metal detector. Once the metal detector had picked up a signal the searcher dug into the beach face to relocate the tracers. Unfortunately, background metal contamination on beaches commonly interferes with recovery signals from aluminium tracers. A further problem was retrieving the aluminium tracers at depth in the beach face, as the structure and compaction of the beach face were disturbed it was easier for buried tracers to move in subsequent tides. The density of the aluminium tracers is not compatible to all compositions of pebble and the artificial pebbles were rounder and possess a lower surface roughness than many indigenous pebbles.

The distinct advantage of the aluminium tracers was that they were detected below the beach surface to depths of 0.35-0.50 metres according to the size and orientation of the tracers. Investigation of the depths to which tracers are buried enables a three dimensional study of beaches to be made. Bray (1996) has improved the aluminium tracer technique by increasing the depth to which the aluminium tracers are detected. Furthermore, smaller aluminium pebbles have been manufactured enabling a greater proportion of the pebbles composing the beach to be modelled (Bray and Copper 1996).

ELECTRONIC TRACERS

Electronic tracer pebbles are the most advanced form of pebble tracers to date. The tracers were developed at the University of Southampton. The experimental efficiency of the electronic pebbles was reviewed by (Workman et al. 1994).

A electronic circuit was encapsulated in resin and moulded to conform to the density, shape and size of the pebbles, on Shoreham beach Sussex. The enclosed circuit transmitted an individually coded signal in response to radio signals. Recovery of the electronic pebbles in the beach environment was undertaken using a radio transmitter device on a wheeled detector frame, that provided a quick method of covering the beach zone and a higher tracer recovery was achieved. Radio transmission signals were sent to earphones and a hand held microprocessor system transformed the radio transmitter signals into pebble frequencies. The strength of the received signal provided an estimation of the depth to which the tracer was buried, however the orientation of the tracer complicated the depth estimation.

The distinct advantage of electronic tracers are they are not susceptible to false contacts with other metal detritus and high tracer recoveries increase the accuracy of the sediment transport predictions. Further modification of the electronic tracers has enabled a wider spectrum of pebble shapes to be modelled and the electronic circuit has been reduced so that slightly smaller electronic pebbles can be manufactured (Lee 1996).

This review highlights that there are numerous tracer techniques available, that vary in application, degree of sophistication and cost. Clearly, electronic pebbles are the most advanced technique of tracing to date. With certain modifications the electronic pebble will become a highly valuable tool for modelling pebble behaviour and transport. In the future, it is envisaged that the depth and code of the electronic tracer will be calculated without the need to excavate into the beach face. This will provide important insight into longshore transport rates with depth. Furthermore, the recording of continuous paths followed by electronic tracers would be very informative.

Unfortunately, due to the limitations of the research funds electronic pebble tracers were too costly for the study reported in this thesis. No artificial tracer could encompass the variance in the composition and the density of the pebbles on the mixed beach at Wemyss. The most accurate and informative tracing technique for the research reported here involved the selection of pebbles from the beach system, which were then painted. This ensured that the tracers modelled the variance in the composition, size and shape of the pebbles on the mixed beach. The following section highlights in greater detail the method of tracer deployment and the procedure for interpreting the tracer data, to ensure that the full potential from the tracer technique is achieved.

5:1 PEBBLE TRACER EXPERIMENT PROCEDURE

AIM 'TO EXAMINE THE RESPONSE OF TRACER PEBBLES OF DIFFERENT COMPOSITION IN WAVE ACTION'

The beach near the Michael colliery is composed of pebbles with a variable proportion of sand. The pebbles on the beach vary widely in composition, shape, size and density. As the shape and density of the pebbles are controlled by the composition, it was proposed that the transport behaviour of pebbles of different composition would be investigated. Additional smaller experiments were undertaken to assess the transport of the fine pebbles and sand on the mixed beach. The transport of pebbles was investigated by means of tracers. Pebbles of different composition were selected from the beach and marked in a way so that when deployed in the beach system the marked pebbles could be detected and the transport could be monitored.

Objectives

1-To monitor the transport rate and direction of pebbles of different composition in a range of wave conditions.

2-To record the cross shore position of the pebble tracers with respect to the beach micro-topography and the high water mark in a range of tidal conditions.

3-To quantify the longshore transport rates for the pebbles of different composition.

Pebbles of three particular compositions were selected for the tracers. Sandstone pebbles were selected to model the indigenous composition of the pebbles on the beach. Ironstone pebbles were selected for tracing, to assess the response of pebbles of high density in wave action. The third type of tracer pebbles selected were composed of the coal waste material. The coal waste consists of coal, refractory shale and sandstone, brick and clinker. The coal pebbles had a light density, in particular the clinker as it possessed an open vesicular texture.

To ensure that the shape and size of the pebble tracers modelled the beach pebbles, a representative beach sample was collected. A Wolman grid(1954) with the dimensions 1x1 metre was placed on the beach face at different cross shore and longshore positions. The size and shape of the pebbles on the beach surface at each grid line intersection were recorded. As a result of the investigation the size of the tracers selected for this experiment varied between 4 and 6 cm (the longest diameter the C axis was taken as a measure of size). To take into account the response of pebbles of different shape in transport, a variety of disc, rod, sphere and blade shaped pebbles were selected. This shape classification is that of Zing (1935) (figure 5:1).

After selection the pebbles were coated in a water and abrasive resistant paint. The paint coatings were of minimal and uniform thickness, in order to maintain the physical characteristics of the pebble. Bright colours were selected to assist in the visual recovery of the tracers. To distinguish between the tracers at different deployment sites and to deceiver between pebbles of different composition, contrasting colours were used. The tracer pebbles were then coded with a number using permanent ink, to allow the movement of individual pebbles to be tracked throughout the duration of the experiment. Prior to the release of the tracers, the composition, shape and the size (Caxis) of each coded tracer pebble were noted to assist recording on the beach.

TRACER DEPLOYMENT PROCEDURE

Tracer deployment sites were chosen to enable the transport to be modelled, cross shore and longshore. To do this transects were constructed perpendicular to the shoreline subdividing the beach face at regular intervals (figure 5:3). Along each transect three tracer injection points were selected on the basis of the micro-topography of the beach face.

1-Lower foreshore (low water mark)

2-Mid foreshore (swash zone)

3-Upper foreshore (upper swash zone to high water mark)

At each injection point, 75 tracers consisting of 25 sandstone tracers, 25 ironstone tracers and 25 coal tracers were injected at one pebble depth (3cm) to ensure that the tracers were incorporated into the thickness of the horizontally moving layer of pebbles undergoing longshore transport (figure 5:2) (plate 5:1). The Time Integration Method of deployment of Crickmore (1967) was undertaken, in which a known quantity of tracers were deployed into the beach system at a particular site. After deployment a lag period of a tide allows the tracers to mix with the host pebble population. Thereafter, the changes in the pebble tracer distribution with time with respect to the deployment point were monitored.

WAVE CLIMATE MONITORING

As the tidal cycle influences the migration of the active wave front across the beach face the tracer experiments were undertaken throughout the range of tidal conditions i.e. from the maximum Spring tides to the minimum Neap tides.

Only simple methods could be used to monitor the wave and wind parameters due to the limitations of the research funds. The wave and wind parameters were monitored at regular intervals throughout the tracer surveys and were recorded on an Excel Field Sheets. The breaking wave heights were recorded visually with

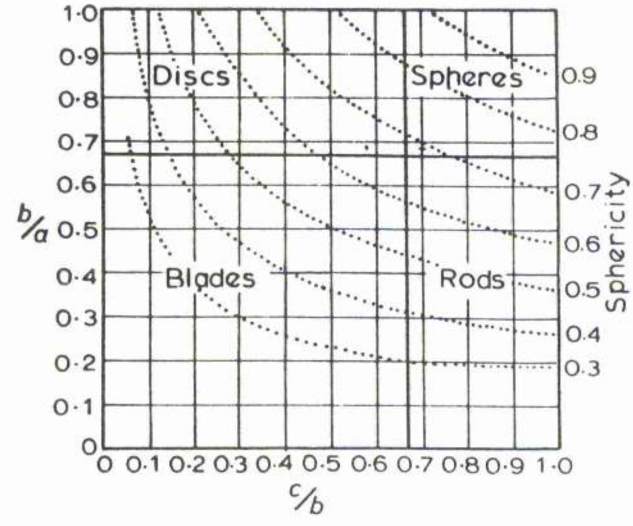


Fig 5:1 Zing shape classification (source Briggs, D. 1977).

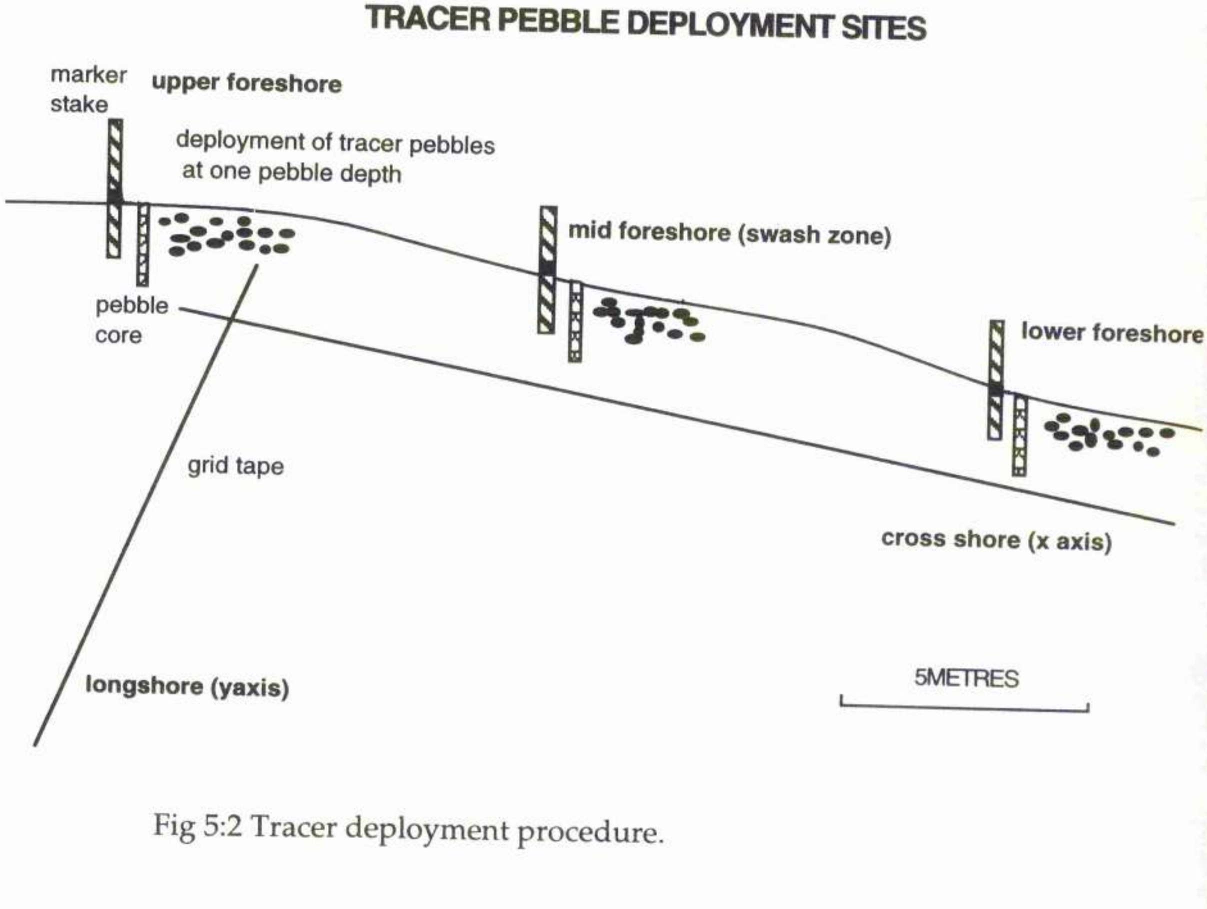


Fig 5:2 Tracer deployment procedure.

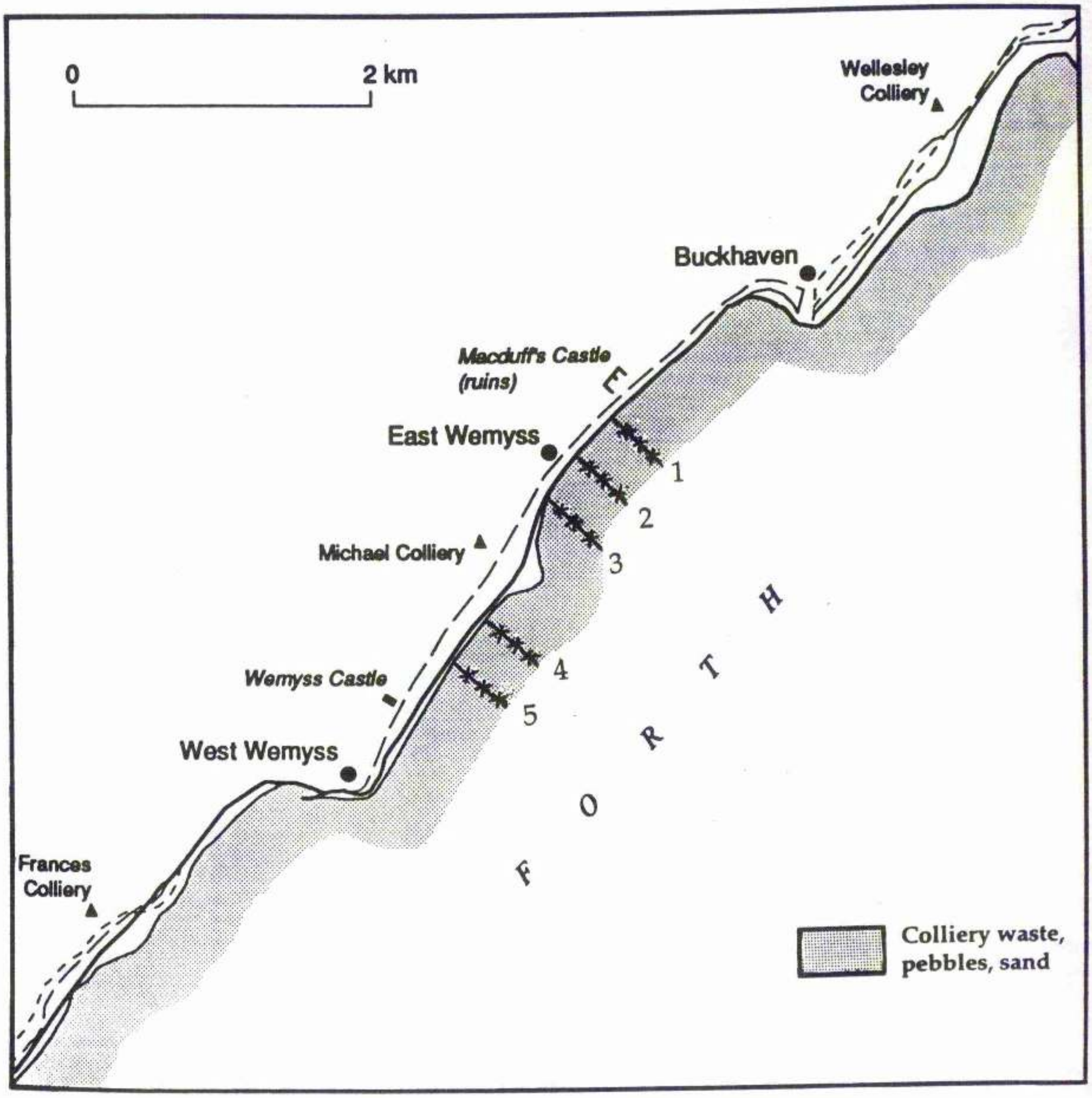


Fig 5:3 Location of the transects for tracer deployment.

a graduated pole at a fixed location at low water. From these the root mean squared wave height $(rms)^2$ was calculated for each tide. A more accurate measurement of wave height requires a pressure transducer, which logs the wave data over time. The wave period or frequency represents the number of wave crests passing a given point over a set period of time. A stop watch recorded the wave counts for a minute. Repeated wave counts were made whilst the tracers were subjected to wave action, then a mean wave period was calculated for each tide. The angle of wave approach was determined from a hand held compass aligned with respect to the shoreline. The wave angles were recorded with respect to the direction from which the waves were approaching. The type of wave breaker was assessed from visual observations and the length of swash runup after breaking was measured using a tape measure positioned perpendicular to the wave uprush direction. This established the width of beach over which the tracers were spread.

The wind speed data was recorded in miles per hour with a hand held wind gauge. A compass recorded the direction from which the wind was blowing. Supporting wind data was collected from the Fife Ness meteorological station. In addition, Fetch data for the particular area was gathered from a report by McManus (1990) and bathymetric charts were studied for information on refraction (Firth Admiralty chart 734). The tidal current data was collected from a report by HR Wallingford (1994).

RECOVERY OF THE TRACER PEBBLES

Following each tide, tracer searches were undertaken at low water. Tracer recovery was restricted to the surface of the beach as the painted tracers could only be detected visually. As the time for the searches was restricted by the next incoming tide, a systematic method of recovery was essential. The searches were made in transverses running parallel to low water, over the area of a predetermined search grid. The longshore and cross shore position of the tracers were recorded on the grid in relation to the deployment site (plate 5:2). This involved the use of two tape measures one on the Y axis to measure the longshore tracer displacement and one along the X axis to measure the cross shore displacement (plate 5:3). This gave a time average distance of transport in one tide. On recovery the tracers were positioned with respect to the beach micro topography and the high watermark. Prior to the experiment beach profiles were taken using the EDM at Spring tides and throughout the experiment smaller scale changes in the beach micro topography were assessed using a clinometer and a tape measure which extended from high to low water. After each tracer search the tracers were left in the positions from which they were recovered. The tracers were not returned to the initial deployment point, as the tracer codes allowed the

Plate 5:1 Deployment of the pebble tracers.

Plate 5:2 Procedure for positioning the tracers after deployment.

Plate 5:3 Tracer recovery.

longshore and cross shore transport pathways to be monitored on subsequent tides for the individual pebbles. Throughout the duration of the survey the tracers recovered were given as a percentage of the initial deployed tracer total. Buried tracers and tracers lost offshore had to be taken into account. However, the individual codes enabled buried tracers that were subsequently re-exhumed to be identified. Tracer searches were undertaken until the tracer recovery rates were too low to be significantly viable (<30%) or until adverse weather conditions restricted the experiment duration.

From the tracer results the mean longshore transport for the sandstone, coal and ironstone pebbles were calculated for each tide. The mean tracer transport in one tide was then correlated with the wave parameters and represented in graphic form. An empirical sediment transport formula was then applied to quantify the velocity and volumetric transport of the three compositions of pebble. The quantification procedure incorporated the results from experiment two (section 7:13).

5:2 SEDIMENT TRANSPORT QUANTIFICATION PROCEDURE

Quantification of the tracer data established the velocity and volumetric transport of the sandstone, coal and ironstone pebbles.

THE VELOCITY OF TRACER TRANSPORT

To determine the velocity of pebble transport, the longshore tracer centroid was defined. The centroid represents the mean distance of transport of the pebble tracer relative to the deployment site in a given unit of time. The longshore and cross shore co-ordinates of the tracers were recorded after each tide and a mean transport for each tide was then determined. To calculate the velocity of tracer transport the unit of time during which the tracers were subjected to wave action needed to be specified. This unit of time was dependent on the tide level, the beach profile morphology and the wave climatic conditions. Ideally, for the highest accuracy reference to ordnance datum is required. For this survey a standard of 4 or 5 hours for each tide was used, according to the tide and wave conditions. The calculation below determines the mean tracer transport longshore and cross shore with respect to the injection site U_S (m/s);

$$Us = X_{(\text{cross shore})} \sum_{1}^{n} \frac{Xn - Xo}{n} / t \quad Y_{(\text{longshore})} \sum_{1}^{n} \frac{Yn - Yo}{n} / t$$

(Equation 5:1)

X Y co-ordinates of the tracer centroid

Xo Yo co-ordinates of the injection site

Xn yn co-ordinates of each pebble used in the calculation

n number of pebbles used

t time tracers subjected to wave action

VOLUMETRIC PEBBLE TRANSPORT

The volume of sediment transported alongshore beyond the deployment site is represented by Q (m^3/s). The simple calculation is given below;

$$Q = U_S \; M \; N \qquad \text{(Equation 5:2)}$$

U_s is the velocity of the tracer transport (m^3/s)

M mean width (m) N mean depth (m)

M refers to the mean width of the mobile sediment layer undergoing longshore transport. This is established from the mean width over which the tracers were spread. Specifying the width of a beach system is difficult as a beach has a finite cross sectional area which is not easily defined especially at the seaward limit. However, boundaries are required for the application of the equation. The width was therefore considered to be bounded by the seaward limit of breaking waves and the limit of uprush on the beach, that was dependent on tide level.

N is the thickness of the layer of sediment undergoing longshore transport. The mean disturbance for each tide was established from the cross shore and longshore vertical pebble cores (section 7:13).

The tracer results were incorporated into empirical longshore transport formula (CERC Coastal Engineering Research Center - Shore Protection Manual 1984). The formula assumes that the sediment transport is functionally dependent on the wave breaker height. For sediment to move in the longshore direction the waves are required to break at an angle to the shore. When the wave approach is oblique only a certain proportion of the wave power is deflected alongshore direction and exerted on a unit length of beach. This component of wave power is termed the wave energy flux, with the units (Newtons/m-1(shorelength) tide -1) ;

$$P1_b = \frac{p\,g}{16} \; H_{b(rms)}{}^2 \; C_b \; \sin 2\,\alpha_b \qquad \text{(Equation 5:3)}$$

p density of seawater (1,025kg/m^3)

g acceleration due to gravity which is 9.8 (m/s^2)

$H_b\,(rms)^2$ root mean square wave breaking height

C_b wave celerity or speed at wave breaking (m/s) $C\sqrt{gd}$

d wave depth (m) : assuming $\frac{H}{d} = 0.78$

α angle the wave crest and line parallel to the shoreline

The immersed sediment transport rate refers to the weight of transported sediment when submerged in water, the equation takes into account the variations in the density and porosity of the beach;

$$I_l \ (p_s - p) g \ \ a \ Q \qquad \text{(Equation 5:4)}$$

I_l immersed longshore sediment transport rate (m^3/s)

p density of water ($1{,}025 kg/m^3$)

p_s coal - 2,000 (kg/m^3), sandstone - 2,650(kg/m^3) ironstone - 2,900(kg/m^3). The density was calculated by measuring firstly the dry weight of the pebbles, then the displaced volume of water when sumerged. The volume of water was then calculated into a mass.

g acceleration due to gravity ($9.8 m/s^2$)

a porosity factor which accounts or packing coefficient (0.6)

Q volumetric transport (m^3/s)

The immersed sediment transport is then empirically related to the 'wave energy flux (P_{lb}) 'by including a dimensionless coefficent K;

$$K = \frac{I_l}{P_{lb}} \qquad \text{(Equation 5:5)}$$

Where K is the coefficient of proportionality, describing the efficiency of energy transfer from the wave power imposed on the beach and its a ability to move sediment. Early calibration of the CERC formula by Komar and Inman (1970) derived a longshore transport coefficient K for sand beaches with a mean value taken as 0.78. Subsequent calibration yielded a coefficient K 0.42 which utilised the root mean squared breaking wave height $(rms)^2$ that was believed to be a better approximation than the specific wave height. On a pebble beach the coefficient K for the longshore transport of sand would over estimate the volumetric longshore transport rate for pebbles. Pebbles were found to move longshore at approximately 3-4 metres a day under normal sea conditions. Bray (1990) recalculated K values using aluminium pebble tracers and established a values of K ranging between 0.021 and 0.06, which was considerably lower than the predicted value for sand beaches. Subsequent, experiments by Nicholls and Wright (1991) at Hurst Spit calculated K coefficient ranging between 0.005 to 0.1 which highlights the possible range in the value of K.

There are more complex sediment transport formulae such as that of Ackers and White (1973) and Bijker (1971). The complex formulae require detailed knowledge of the various wave and sediment input parameters, however they are valuable when studying sediment transport in detail or under controlled conditions. Bijker (1971) incorporates size and size related parameters, in addition to a roughness coefficient, whereas in the CERC formula the particle size and related parameters are assumed to be uniform. This research appraises how well the CERC formula can be applied to a mixed beach.

6:1 THE RESPONSE OF TRACER PEBBLES OF DIFFERENT COMPOSITION IN WAVE ACTION

Between April and September repeated deployments of coarse tracer pebbles of a range of compositions were made in the beach system. This ensured that pebble transport was examined for a wide variety of possible wave and wind variables. The collection of the tracer data also took into account the two tidal extremes, the maximum Spring tides and the minimum Neap tides. Throughout the tracer surveys the wave conditions were typical for the time of year, with only occasional short storm events relating to low pressure systems. The sediment transport rates would be significantly greater in the winter period, when wind and wave activity is greater.

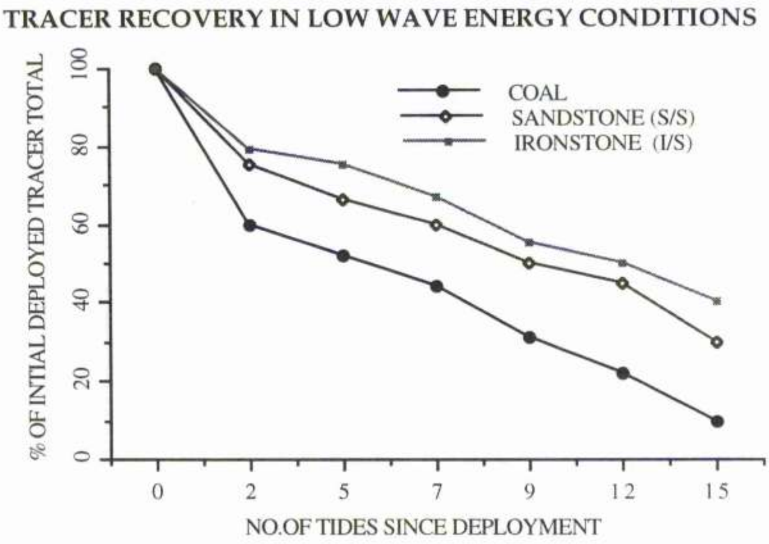
The mean longshore transport rates and directions of the sandstone, ironstone and coal tracer pebbles were calculated for each tide and represented according to the sector from which the breaking waves approached (Table 6:1). Appendix 6:A is a wave rose compiled from the data recorded in the tracer surveys. When the waves were from the east the transport rates were given positive (+) values, whereas, transport rates associated with waves from the west were given negative (-) values. The mean pebble transport in one tide was then correlated to the wave height, wind speed and the wave energy flux, reference is made to figures which focus on particular trends of interest. The significance of the correlations was represented by the regression values. Visual observations of the pebbles in transport were also highly informative.

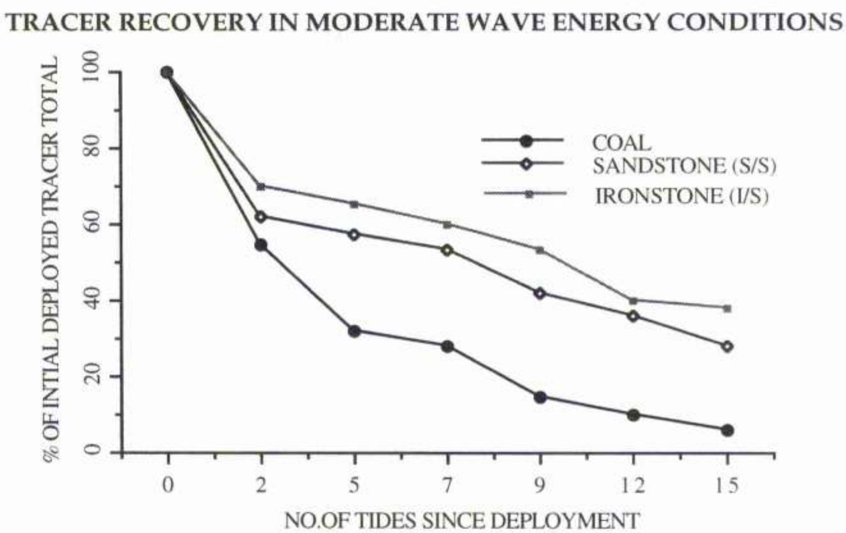
WAVE SECTOR	WAVE ANGLE	MEAN ANGLE	MAX FETCH KM	MEAN FLUX N/m/s
SOUTH	140-200	+5 / -5	<10	92
SOUTHEAST	90-140	+15 to +25	430	409
EAST	50-90	+25 to +35	370	933
SOUTHWEST	200-270	-10 to -20	18	300

Table 6:1 Wave parameters according to the sector from which waves approach the Wemyss beach (figure 2:23).

To analyse the tracer data further, a series of quantification procedures were undertaken as outlined in section 5:2. The mean transport velocities of the three compositions of pebble were calculated (Us m/s), the volumetric transport rates of the pebbles (Q m^3/s) were calculated by multiplying the tracer velocity by the mean disturbance of the beach face (vertical core data section 7:13) and by the width of beach over which the tracers had spread. The results are represented in Appendix 6:B.

The CERC empirical transport formula was applied to establish whether a relationship existed between the pebble transport and the wave parameters.





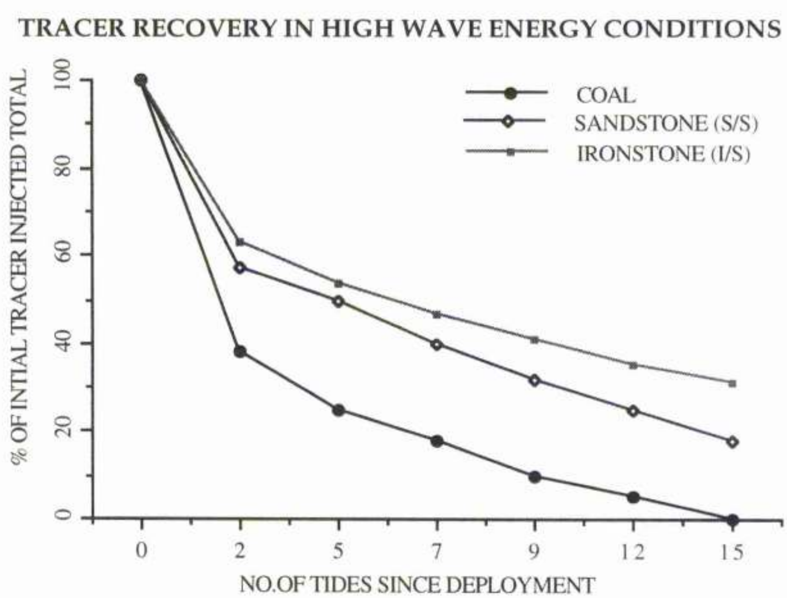


Fig 6:1 Tracer recovery according to the wave energy conditions.

The various stages for the calculation of this formula are illustrated in section 5:2. The wave energy flux (Pl_b) was a measure of the longshore wave power to which the tracers were subjected, a mean value was calculated for each tide. For simplicity, the tracer results are illustrated by subdividing the wave conditions into classes; low, moderate and high wave energy, on the basis of certain wave parameters as outlined below;

WAVE ENERGY	WIND SPEED(MPH)	HEIGHT (RMS)^2	WAV E FLUX (N/M/S)
Low	<10	<0.30	<500
Moderate	10-14	0.30-0.70	500-1000
High	14-20	0.70-1.30	1000-3000

Table 6:2 Wave energy classification.

TRACER TRANSPORT IN LOW WAVE ENERGY CONDITIONS

In low wave energy conditions the tracers recovered represented a significant percentage of the initial total of deployed tracers (figure 6:1). The highest proportion of tracers recovered were composed of ironstone, as 70% of the deployed ironstone tracers were still recovered up to five tides after deployment.

In low wave energy conditions the transport of the ironstone tracer pebbles did not occur until the wave heights reached 0.30 metres and the wind speeds were over 7 miles per hour (figure 6:2). Once the wave heights had reached 0.30 metres the longshore dispersion of the ironstone tracer pebbles in one tide was still limited. Consequently, a high proportion of the tracers showed no movement and remained at the injection site and the ironstone tracers which had moved were recovered within 0-2 metres of the deployment site (figure 6:41a-c). The mean longshore transport of the ironstone tracers in one tide varied from 0.46 to 0.88 metres, according to the sector from which the waves approached (Table 6:3). When waves approached from the south sector, the longshore dispersion of the tracers was more restricted than waves from the other sectors and the highest proportion of ironstone tracers remained at the injection site (figure 6:41b). The southeast waves were responsible for transporting the ironstone tracers further alongshore (figure 6:31). When the wave power exerted alongshore from these southeast waves reached 500 (N/m/s) the maximum transport of the ironstone tracers in one tide was five metres (figure 6:61). However, it was apparent that most low wave energy conditions were associated with locally generated wind waves from the south and southwest which had limited fetches (Table 6:1). Consequently, when low wave conditions prevailed for a significant period of time the mean longshore displacement of the ironstone centroid with respect to the initial deployment site was not very significant. After ten tides the displacement of the ironstone centroid with respect to the deployment site was under ten metres (figure 6:51).

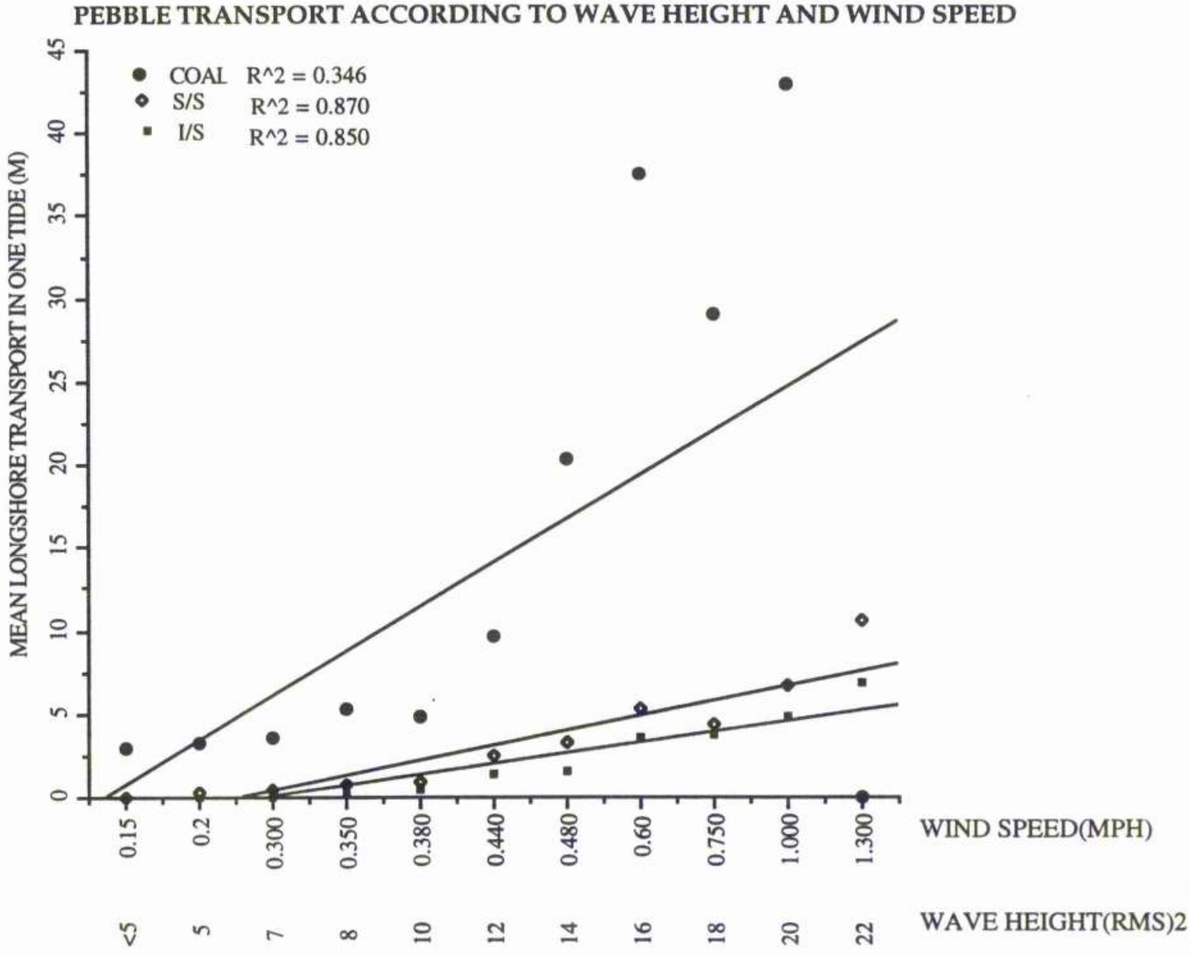


Fig 6:2 Longshore transport according to wave height and wind speed.

TRANSPORT IN ONE TIDE ACCORDING TO THE WAVE SECTOR

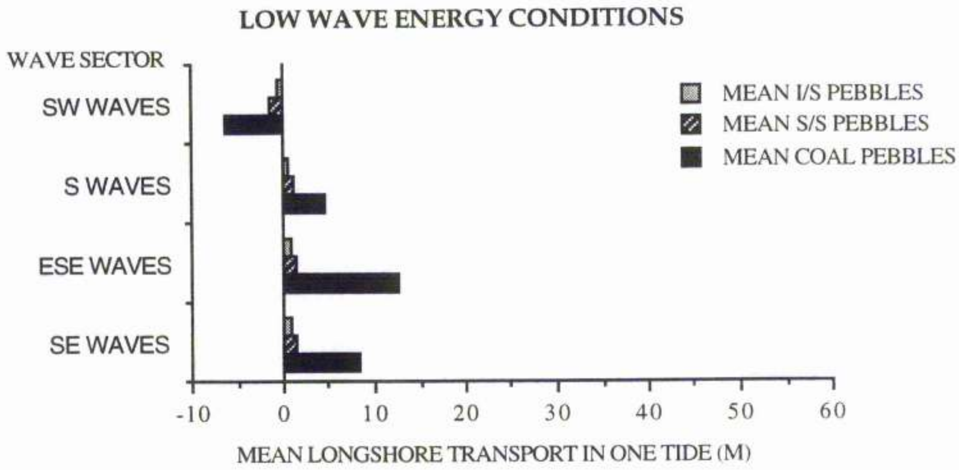


Fig 6:31 Longshore transport low wave energy conditions.

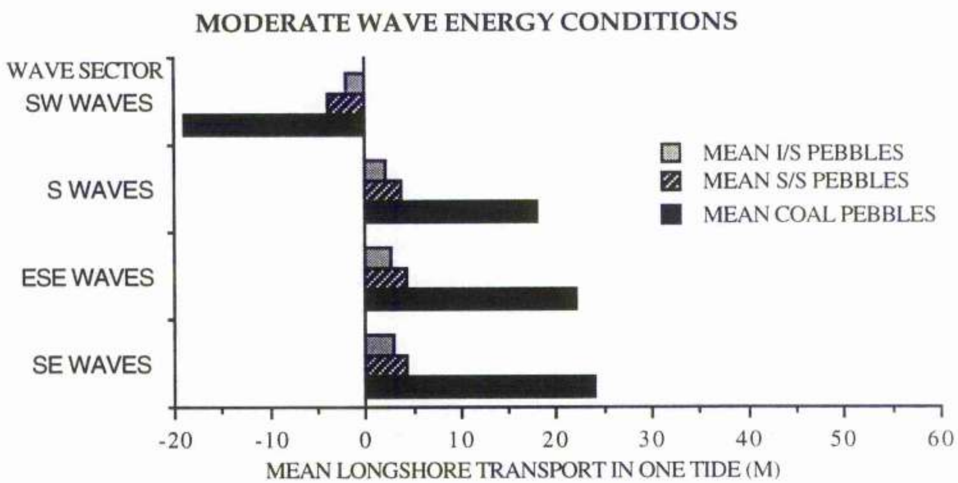


Fig 6:32 Longshore transport moderate wave energy conditions.

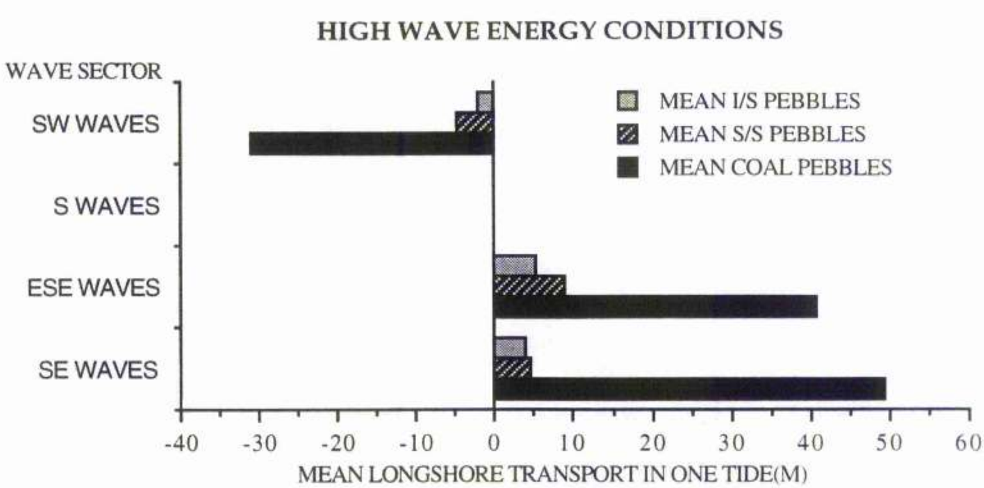


Fig 6:33 Longshore transport high wave energy conditions.

COMPOSITION	WAVES SOUTHEAST SECTOR	WAVES SOUTH SECTOR	SOUTHWEST SECTOR
IRONSTONE	0.88m	0.46m	0.59m (- to east)
SANDSTONE	1.5m	1.28m	1.3m (- to east)
COAL	8.4m	4.5m	6.3m (- to east)

Table 6:3 Mean longshore transport in one tide in low wave energy conditions.

In low wave energy conditions, the sandstone tracers were transported alongshore at wave heights below 0.30 metres (figure 6:2) and a lower percentage of sandstone tracers remained at the deployment site in comparison to the ironstone tracers (figure 6:41a-c). Therefore, it was reasonable to assume that the wave energy threshold for initiating sandstone pebble transport was lower than for ironstone pebbles of similar size. The mean transport of the sandstone tracer pebbles in one tide varied between 1.28 and 1.5 metres, depending on the wave sector (Table 6:3). Waves from the southeast transported sandstone and ironstone pebbles, approximately 0.50 metres further alongshore than waves from the other sectors (figure 6:31). The wave sector also influenced the dispersion of the sandstone tracers which varied from 0.25 metres to a maximum of 18 metres in one tide when waves approached from the southeast (figure 6:41a). Whereas, the maximum longshore transport associated with waves from the southwest, was only 10 metres in one tide (figure 6:41c).

COMPOSITION	MEAN VELOCITY (m/s)	MEAN VOLUME (m/s^3)
IRONSTONE	0.00010	0.000045
SANDSTONE	0.00020	0.00015
COAL	0.00080	0.0009

Table 6:4 Mean velocity and volumetric transport in low wave energy conditions.

In low wave energy conditions the wave power rose to 500 (N/m/s), the transport rate of the sandstone tracer pebbles increased more steadily than the ironstone tracers (figure 6:61/6:62). The quantification of the velocity and the volumetric transport of the indigenous ironstone and sandstone tracers took into account the higher density of the ironstone, that varied from 2,900-3,300 (kg/m^3) whereas, the sandstone pebbles had a density of 2,650 (kg/m^3). In low wave energy conditions, the speed of movement of the sandstone tracers was up to twice that of the ironstone tracers of similar size (Table 6:4). Consequently, when low wave energy conditions prevailed for ten tides the sandstone tracer centroid was displaced 15 metres from the initial deployment site. This distance was up to 8 metres further along the shore than the position of the ironstone tracer centroid, despite the fact the pebbles were of similar size (figure 6:51).

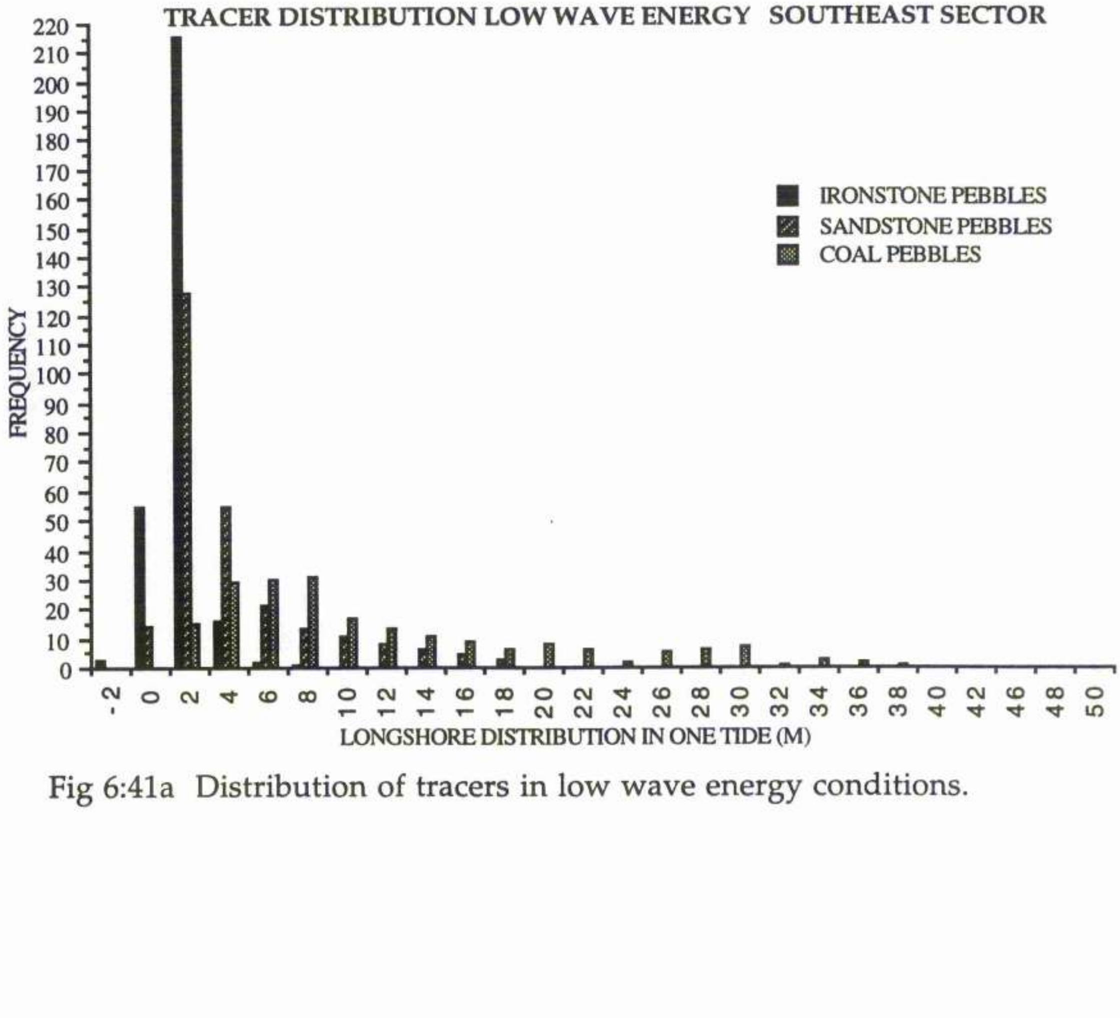


Fig 6:41a Distribution of tracers in low wave energy conditions.

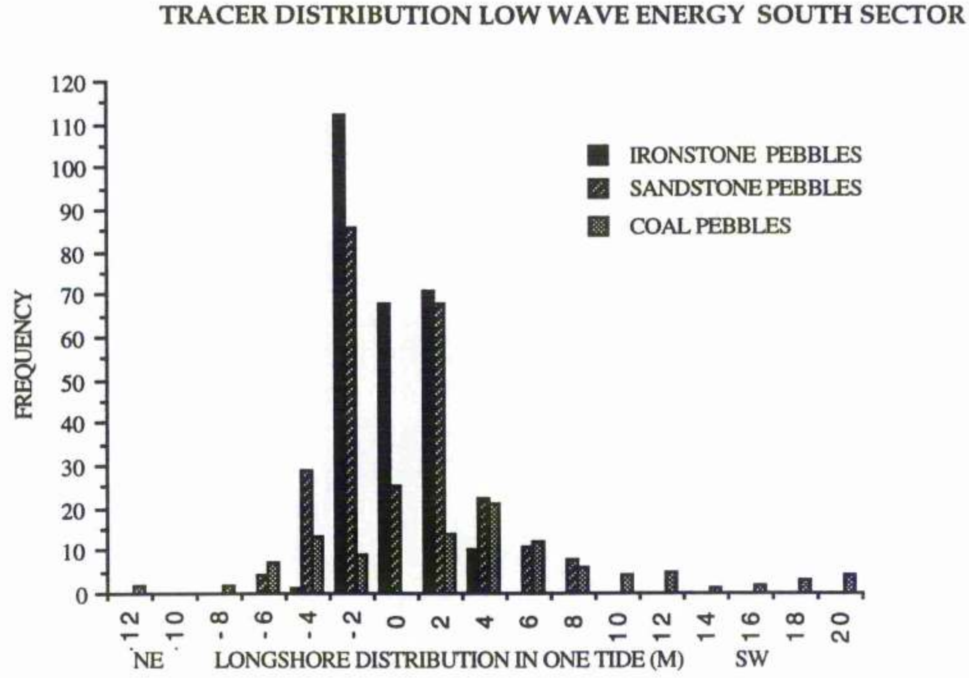


Fig 6.41b Distribution of tracers in low wave energy conditions.

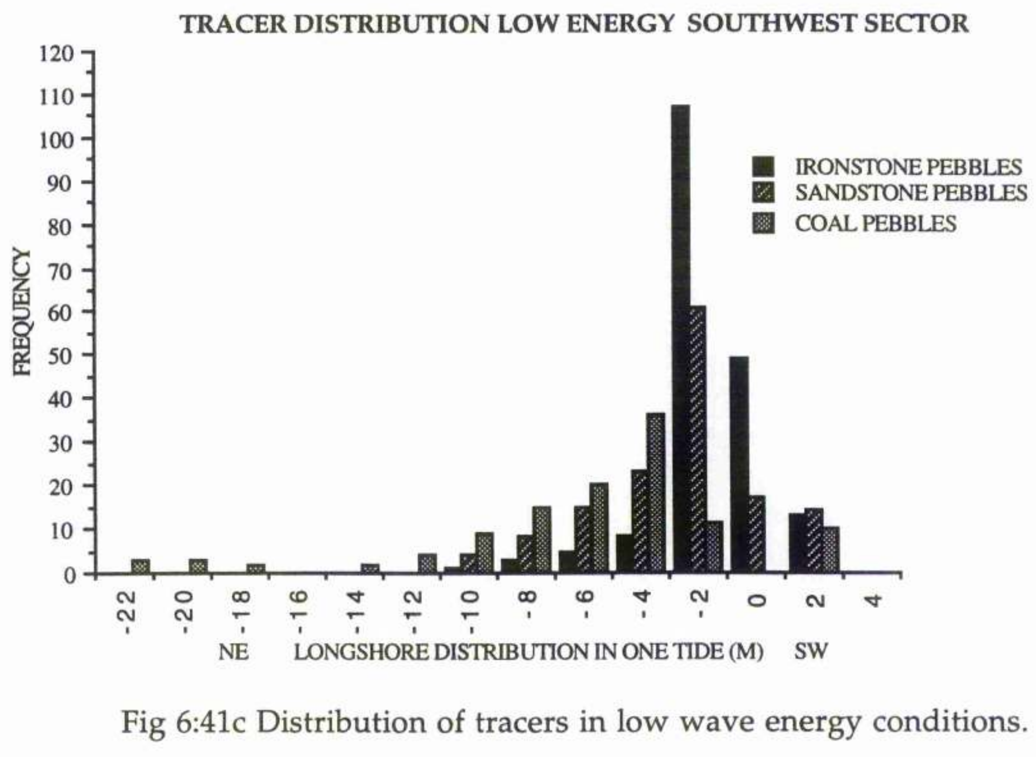


Fig 6:41c Distribution of tracers in low wave energy conditions.

TRACER CENTROID POSITIONS IN LOW WAVE ENERGY

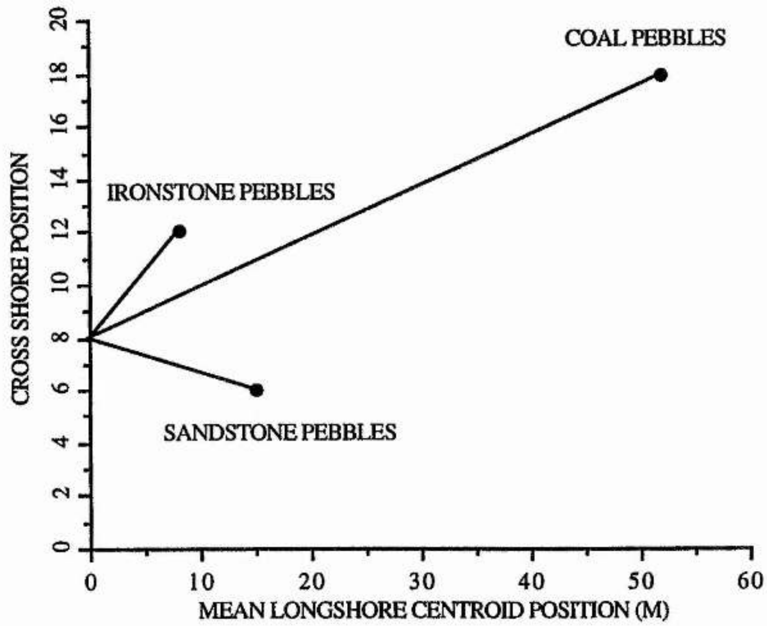


Fig 6:51 Tracer centroid displacement low wave energy conditions.

TRACER CENTROID POSITIONS IN MODERATE WAVE ENERGY

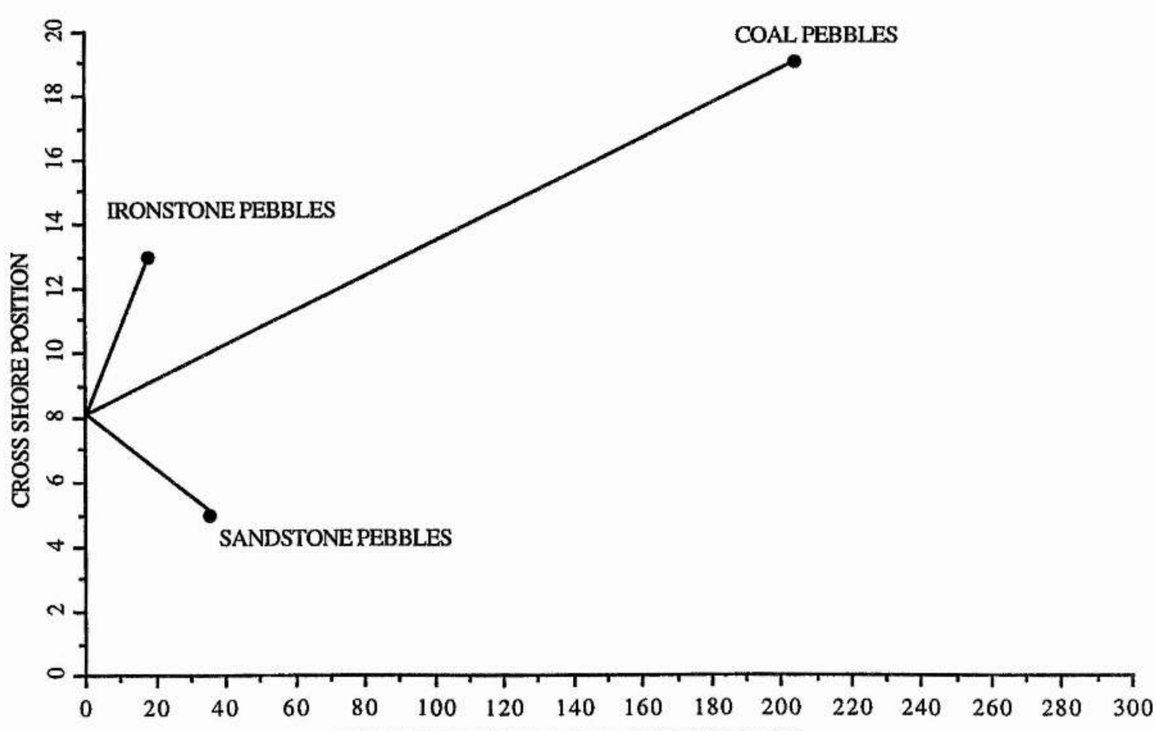


Fig 6:52 Tracer centroid displacement moderate wave energy conditions.

In low wave energy conditions observations revealed that the coal tracers were transported significant distances alongshore, irrespective of the wind speed and at breaking wave heights as low as 0.15 metres (figure 6:2). The coal tracers were dispersed widely throughout the sampling grid area in one tide (figure 6:41a-c). The mean longshore transport rate for the coal pebbles was between 4.5 and 8.8 metres in one tide (Table 6:3). The maximum longshore transport in one tide was up to 30 metres. The transport velocities of the coal tracer pebbles were approximately 4-5 times the mean longshore transport rate of the ironstone and sandstone tracer pebbles of similar size. Consequently, the coal tracer centroid was displaced significantly further alongshore (figure 6:51). After five tides in which low wave energy conditions prevailed, the coal tracers recovered were less than 45% of the initial deployed total. This suggested the coal was already being transported to extreme distances alongshore or offshore by waves and currents (figure 6:1).

TRACER TRANSPORT IN MODERATE WAVE ENERGY CONDITIONS

In moderate wave conditions after two tides the tracer recovered were approximately 65% of the initial tracer deployment total (figure 6:1). The recovery rates decreased throughout the duration of the tracer survey, the most significant decline in the tracer recovery was for the coal tracers. Ten tides after deployment, less than 20% coal tracers were recovered. In contrast, 50% of the ironstone and sandstone tracers were recovered.

In moderate wave energy conditions the wave heights rose from 0.30 to 0.65 metres. There was a clear linear relationship in the mean longshore transport of the ironstone tracer pebbles in one tide, as the wave height increased. The significance of the correlation is indicated by the regression value of R^2 0.85 (figure 6:2). The mean longshore transport for the ironstone tracers in one tide varied between 1 and 2.5 metres according to the wave sector (Table 6:5). The threshold conditions for the longshore transport of the ironstone tracers had been reached (figure 6:32). However, after the dispersion of the ironstone tracer pebbles in one tide, a small percentage of the ironstone tracers still showed no movement (figure 6:42a-c). Observations revealed that many of the ironstone tracers had become buried at the deployment site. The longshore dispersion of the ironstone tracers in one tide, displayed little variation about the mean longshore transport distance. This suggested that the high density of the ironstone pebbles controlled the transport of the tracers.

COMPOSITION	WAVES SOUTHEAST SECTOR	WAVES SOUTH SECTOR	WAVE SOUTHWEST SECTOR
IRONSTONE	2.12m	1.3m	1.55m (- to east)
SANDSTONE	4.1m	3.2m	3.45m (- to east)
COAL	24m	18.1m	18.9m (- to east)

Table 6:5 Mean longshore transport in one tide in moderate wave conditions.

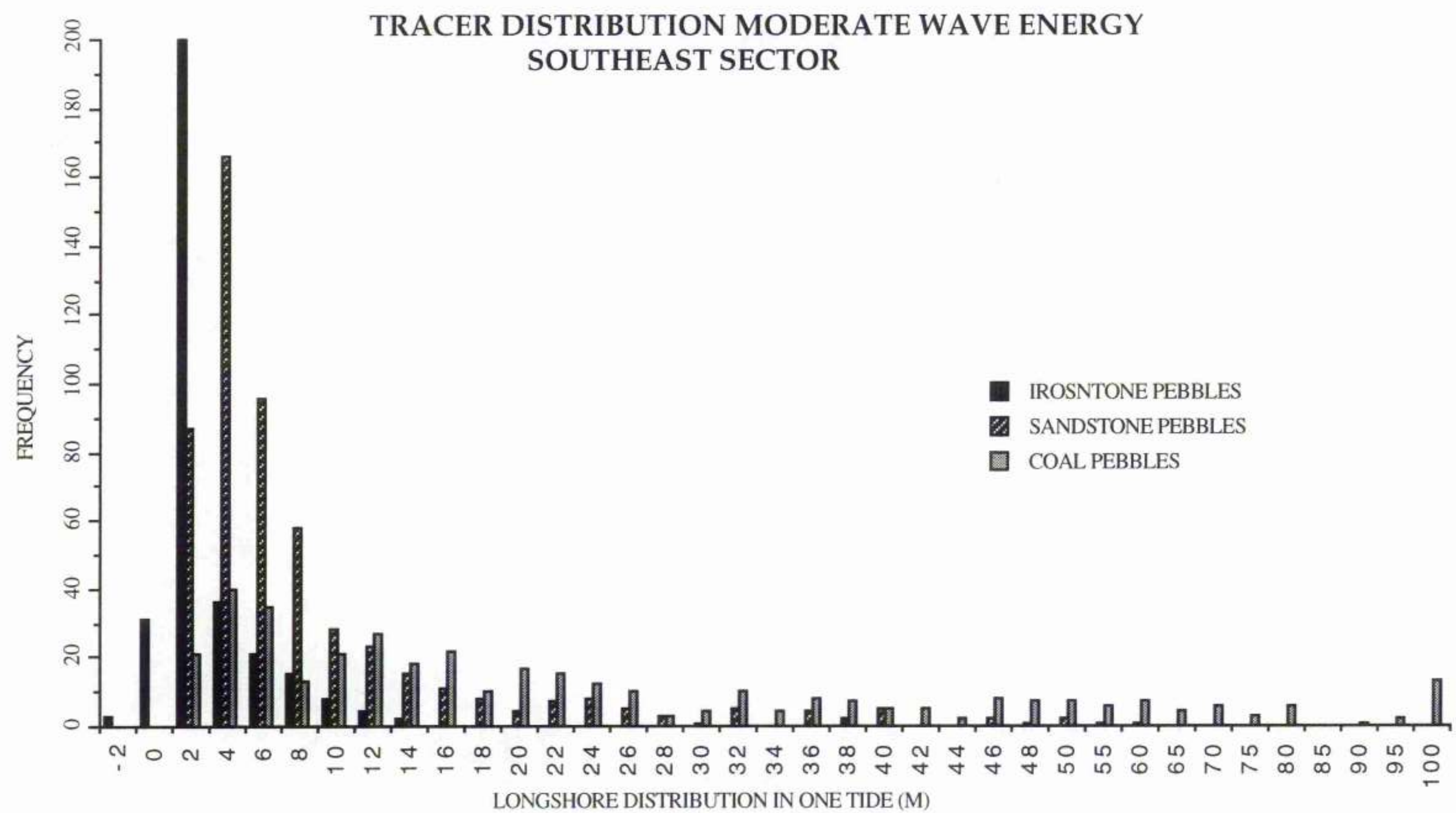


Fig 6:42a Distribution of tracers in moderate wave energy conditions.

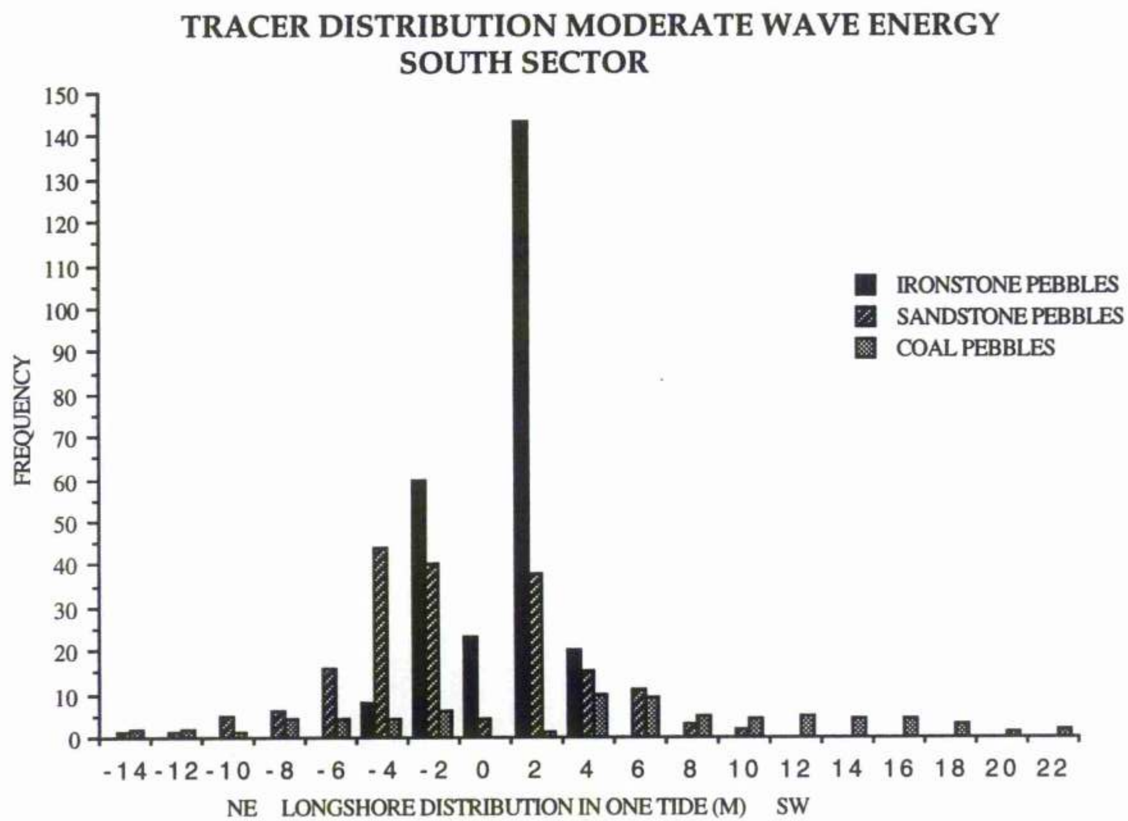


Fig 6:42b Distribution of tracers in moderate wave energy conditions.

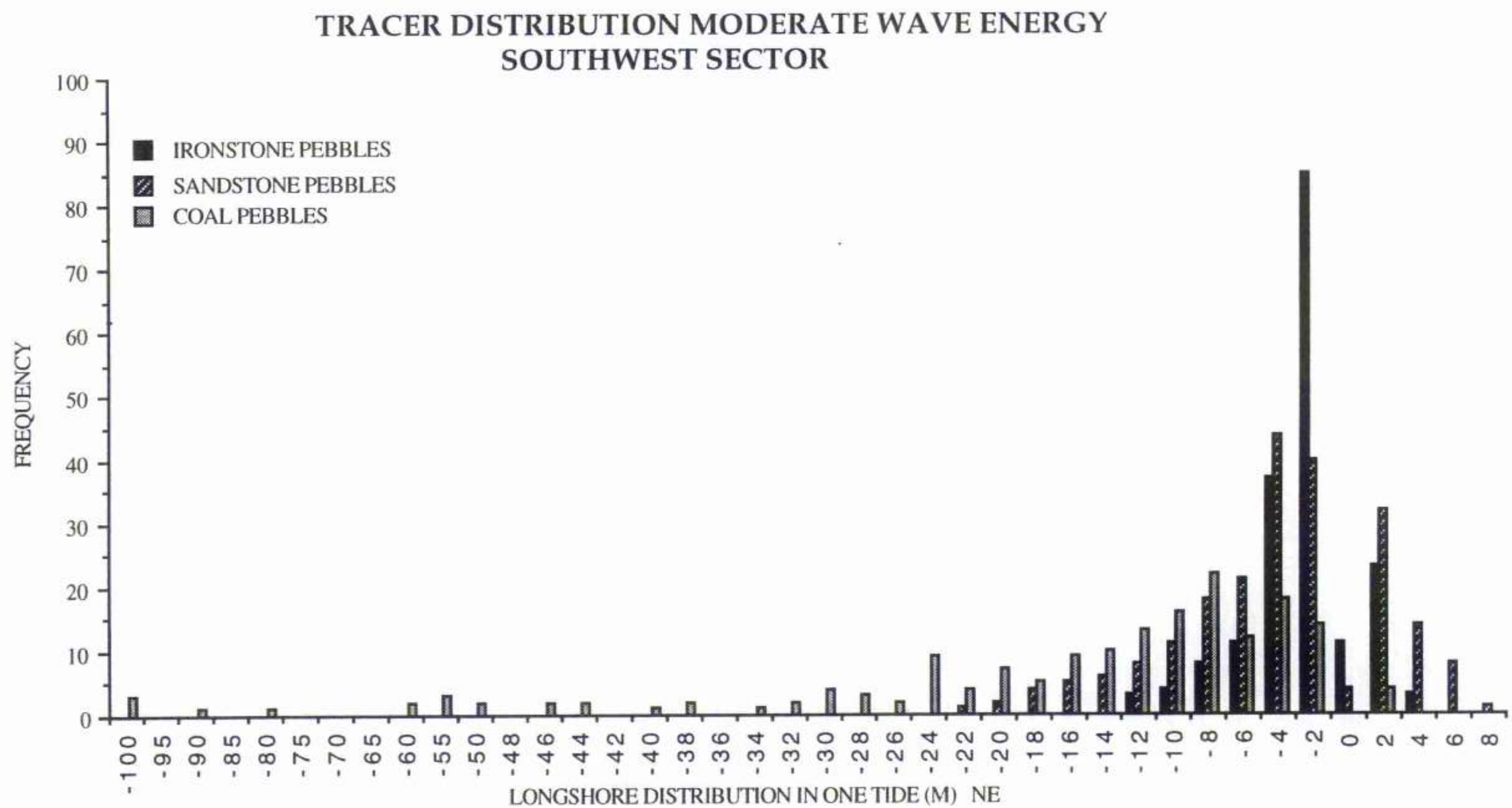


Fig 6:42c Distribution of tracers in moderate wave energy conditions

As the wave power rose from 500-1000 (N/m/s) the mean longshore transport of the ironstone in one tide increased linearly. The strength of the relationship accounts for the high regression correlation value of R^2 0.94 (figure 6:61). The speed at which the ironstone tracers were transported alongshore was significantly greater than in low wave energy conditions (Table 6:6). The maximum longshore transport of the ironstone pebble tracers in one tide was up to 12 metres and corresponded to the dominant southeast wave sector (figure 6:6).

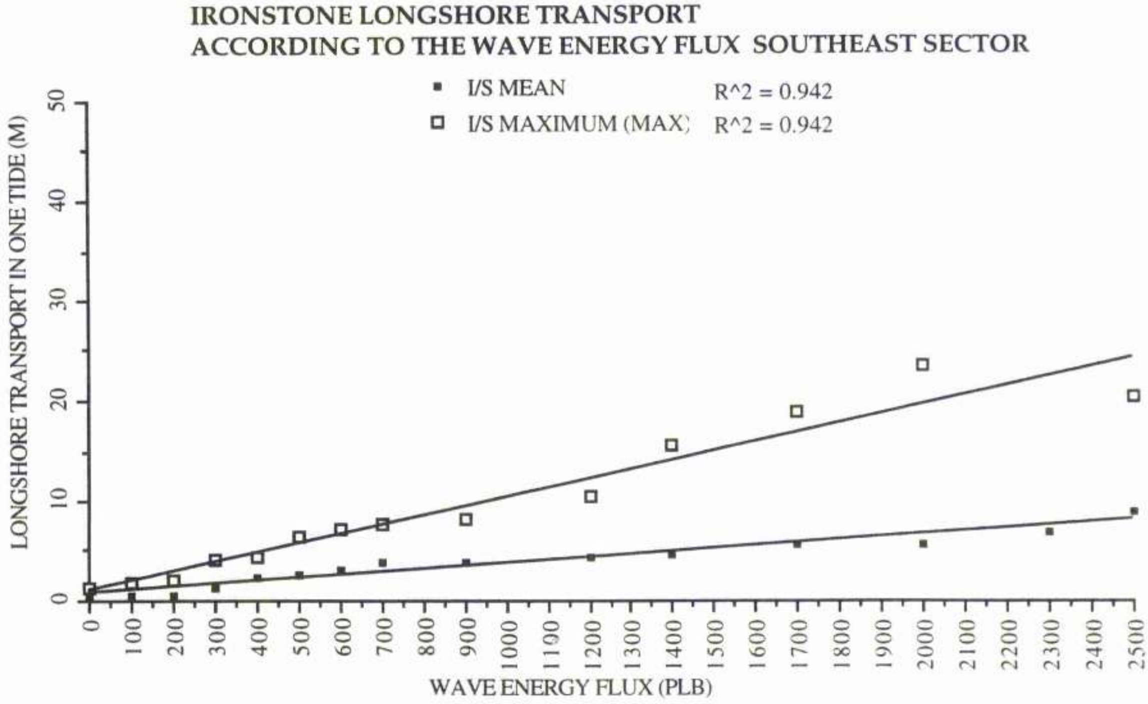
COMPOSITION	MEAN VELOCITY (m/s)	MEAN VOLUME (m/s^3)
IRONSTONE	0.0003	0.00036
SANDSTONE	0.0004	0.00055
COAL	0.005	0.0046

Table 6:6 Mean velocity and volumetric transport in moderate wave energy conditions.

In moderate wave energy conditions when wave heights were over 0.50 metres the mean longshore transport of the sandstone tracers in one tide was between 3.5 and 4 metres. The longshore transport rate for the sandstone tracers increased in conjunction with an increase in both the wind speed and the wave height, the significance of this relationship is indicated by the regression value of R^2 0.87 (figure 6:2). Despite being similar in size, the mean velocity of the sandstone tracer pebbles was 1.5 to 2 times that of the ironstone tracers (Table 6:6). This was attributed to the density difference between the pebbles. The immersed transport rate has a steeper gradient curve for the sandstone tracers than the denser ironstone tracers (figure 6:8). Consequently, when moderate wave energy conditions prevailed for up to ten tides, the sandstone centroid was displaced approximately 17 metres further alongshore than the ironstone tracer centroid (figure 6:52).

In one tide the most significant longshore transport for both the sandstone and ironstone tracers occurred when the waves approached from the southeast sector (Table 6:5). The southeast waves transported tracers up to 0.65 metres further in one tide, than the locally generated southwest waves, and up to 0.90 metres further alongshore in one tide, than waves from the south sector (figure 6:32). The locally generated waves from the south sector displaced ironstone and sandstone tracers either side of the deployment site (figure 6:42a-c).

The mean transport rate of the sandstone tracers in one tide increased linearly with a rise in the wave energy flux. The trend was similar to the ironstone trend, however the rate of transport of the sandstone increased at a faster rate. The transport rate for the sandstone in one tide increased by approximately one metre with an rise of 100 (N/m/s) in the wave energy flux (figure 6:62). The significance of this correlation accounts for the high regression value of R^2 0.95. When waves were from the southwest, a similar correlation occurred between the transport rate



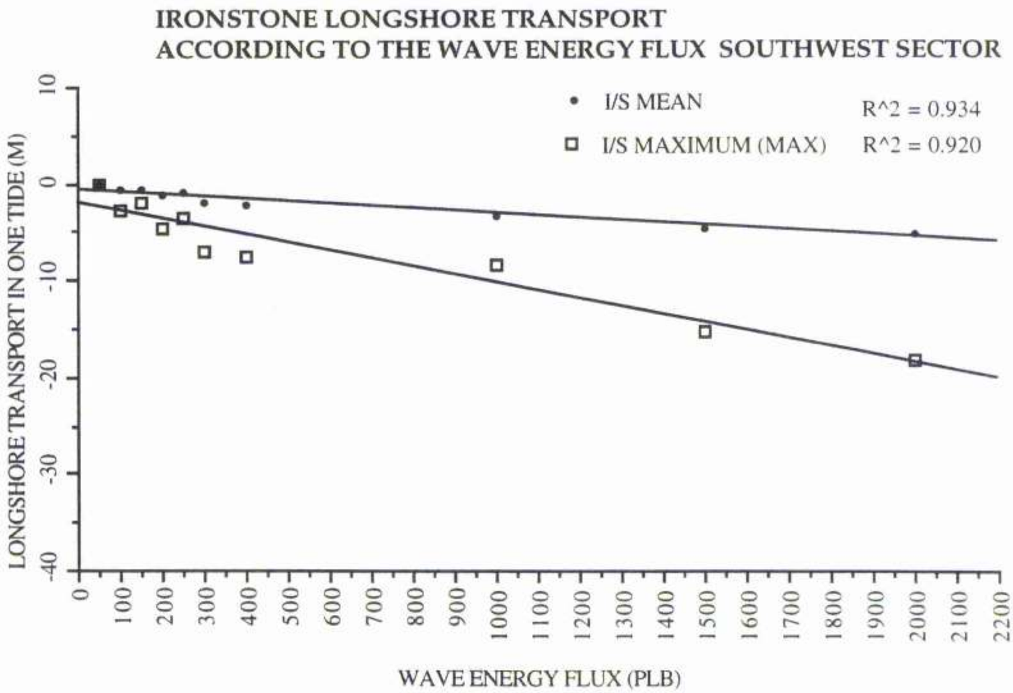
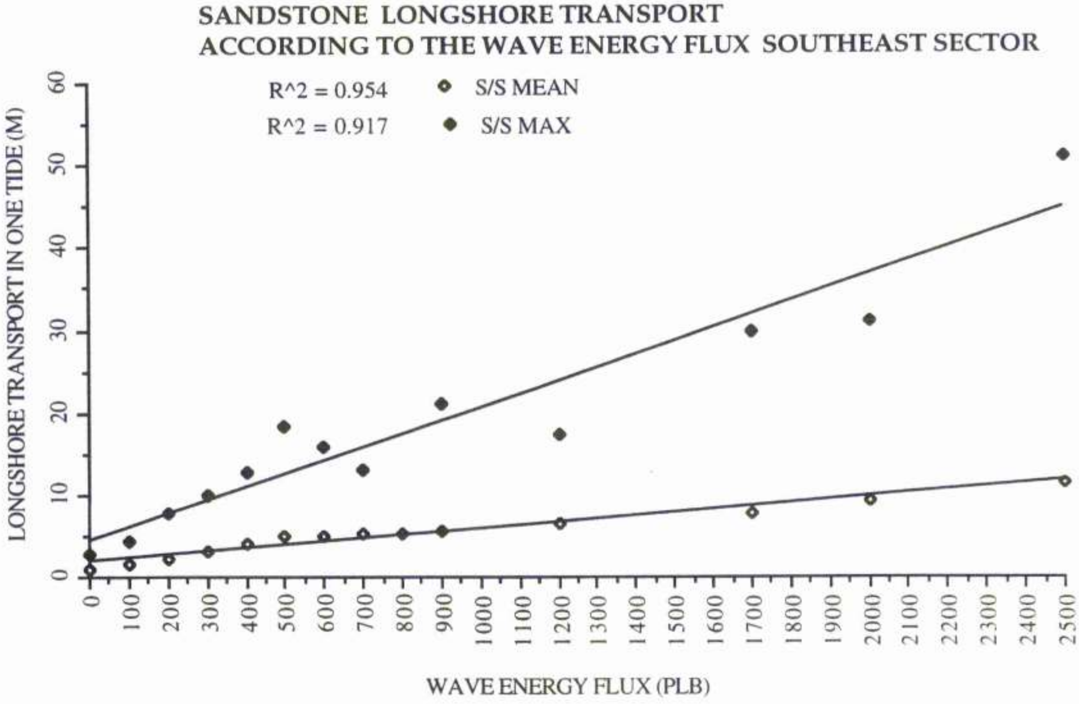


Fig 6:61 Ironstone tracer longshore transport according to the wave energy flux.



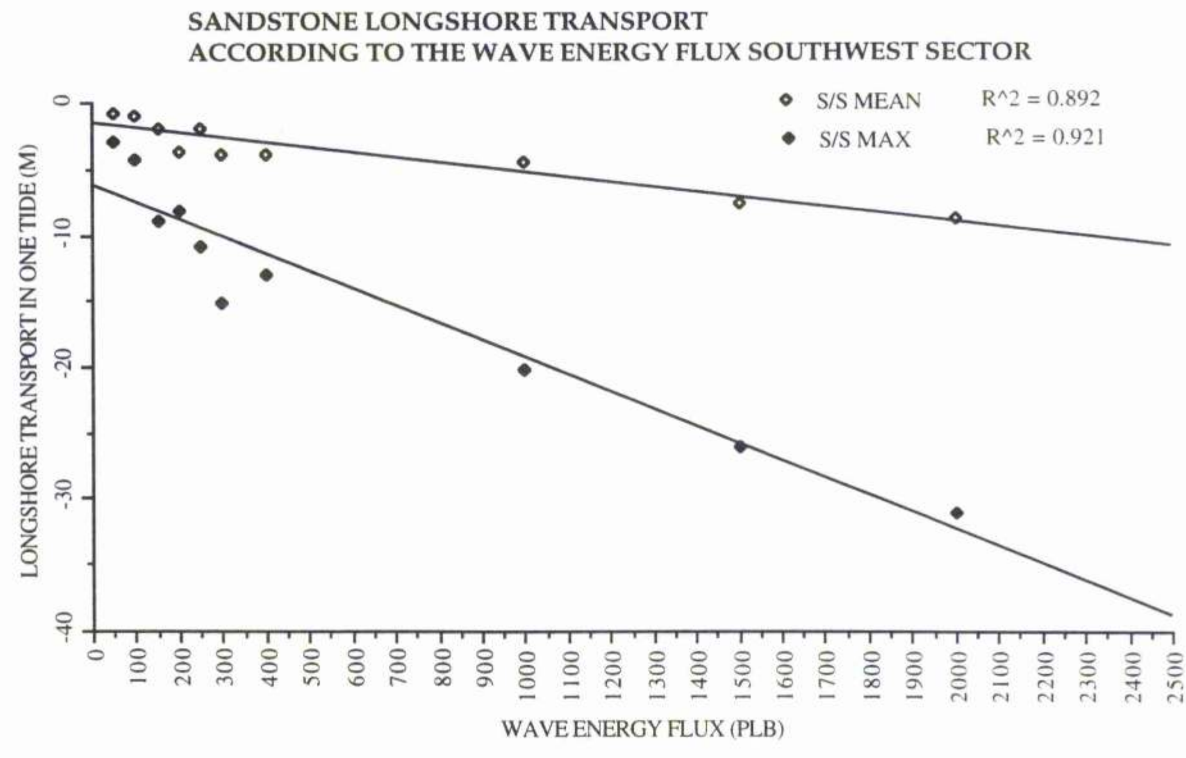
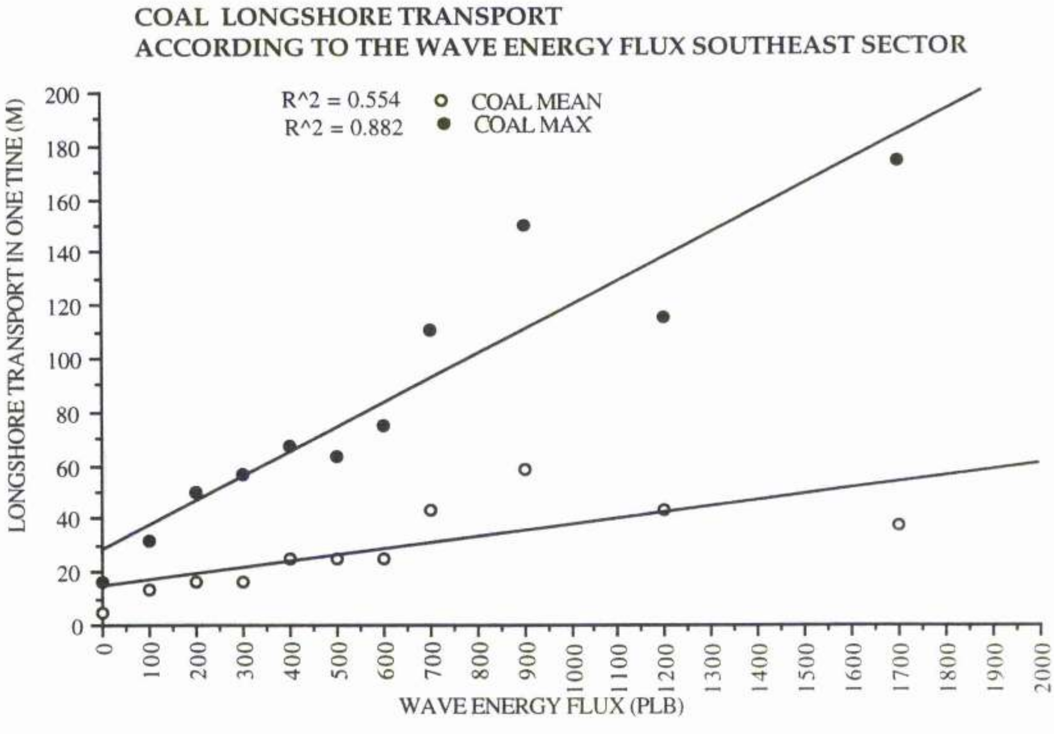


Fig 6:62 Sandstone tracer longshore transport according to the wave energy flux



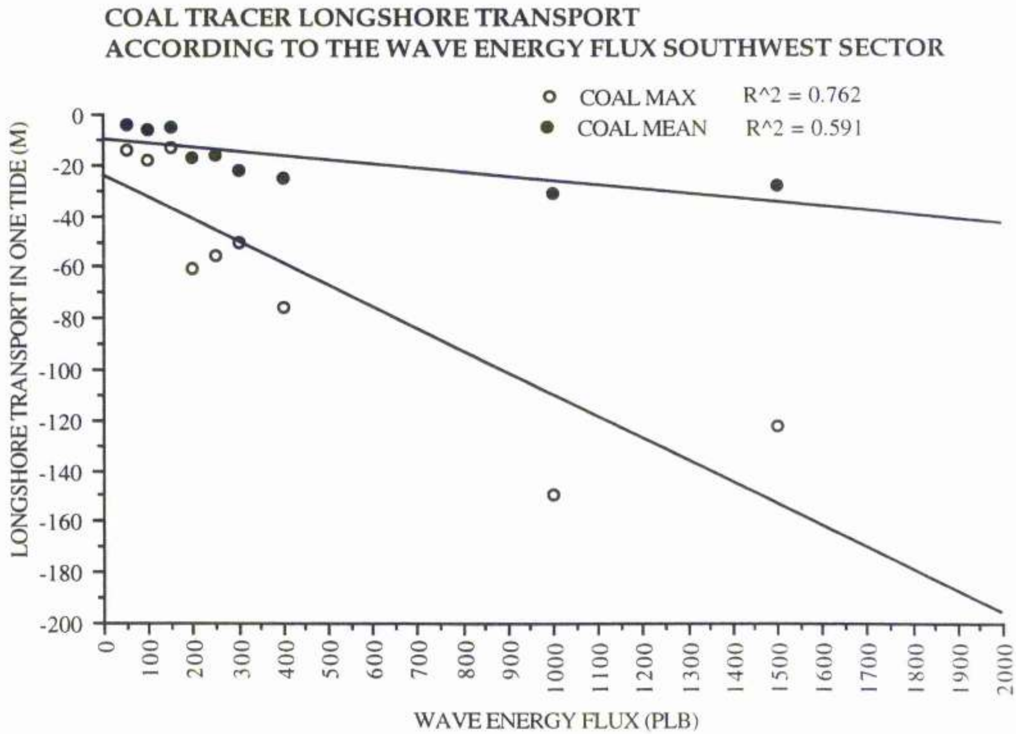


Fig 6:63 Coal tracer longshore transport according to the wave energy flux.

and the wave energy flux, however the wave power exerted alongshore from the locally generated wind waves was less significant.

In moderate wave energy conditions a significant correlation was made between increasing wave energy and the immersed volumetric transport rate, the regression values for the ironstone and sandstone pebbles were R^2 0.87 and R^2 0.86 respectively (figure 6:8). The volumetric transport of sandstone pebbles was three times the rate observed during low wave energy conditions (Table 6:6). The increase in the volumetric transport rate was even more significant for the ironstone tracer pebbles. Both the ironstone and sandstone pebbles were incorporated into the moving layer of sediment undergoing longshore transport.

In moderate wave energy conditions the transport behaviour of the coal tracer pebbles differed markedly to the sandstone and ironstone tracer pebbles of similar size (Table 6:5). The coal pebbles displayed a mean longshore transport that varied between 18 and 24 metres in one tide, according to the wave sector (figure 6:32). However, the mean transport in one tide was misleading, because the coal tracers were dispersed randomly over the entire longshore sampling grid when subjected to waves from all three sectors (figure 6:42a-c). As the wave energy flux increased there was no systematic transport pattern of the coal tracers, therefore the maximum and mean transport of the coal tracer pebbles deviate from the curve fit line and the regression value is low R^2 0.55 (figure 6.63).

The coal tracer pebbles moved considerable distances alongshore, up to a maximum of 150 metres in one tide (figure 6:63). Consequently, the mean coal tracer pebble velocity was 10 times greater than the velocity of the sandstone and ironstone tracer pebbles when subjected to the same wave conditions (Table 6:6). Furthermore, the velocity of the coal tracers was approximately 5 times the velocity recorded in low wave energy conditions, which accounts for the steep gradient of the correlation line as the wave energy increased. The immersed transport rate of the coal tracer pebbles, had a similar steep gradient. The light density of the coal tracer pebbles which was 1,500-2,000 (kg/m^3) enabled a greater volume of pebbles to be transported along the shore (figure 6:8).

By combining the coal tracer data it is evident that some coal pebble tracers were dispersed beyond the extent of the tracer recovery grid. After ten tides in which moderate wave energy conditions prevailed, the mean coal tracer centroid was displaced 6 times further along the shore than the sandstone tracer centroid and 11 times further along the shore than the ironstone tracer centroid (figure 6:52).

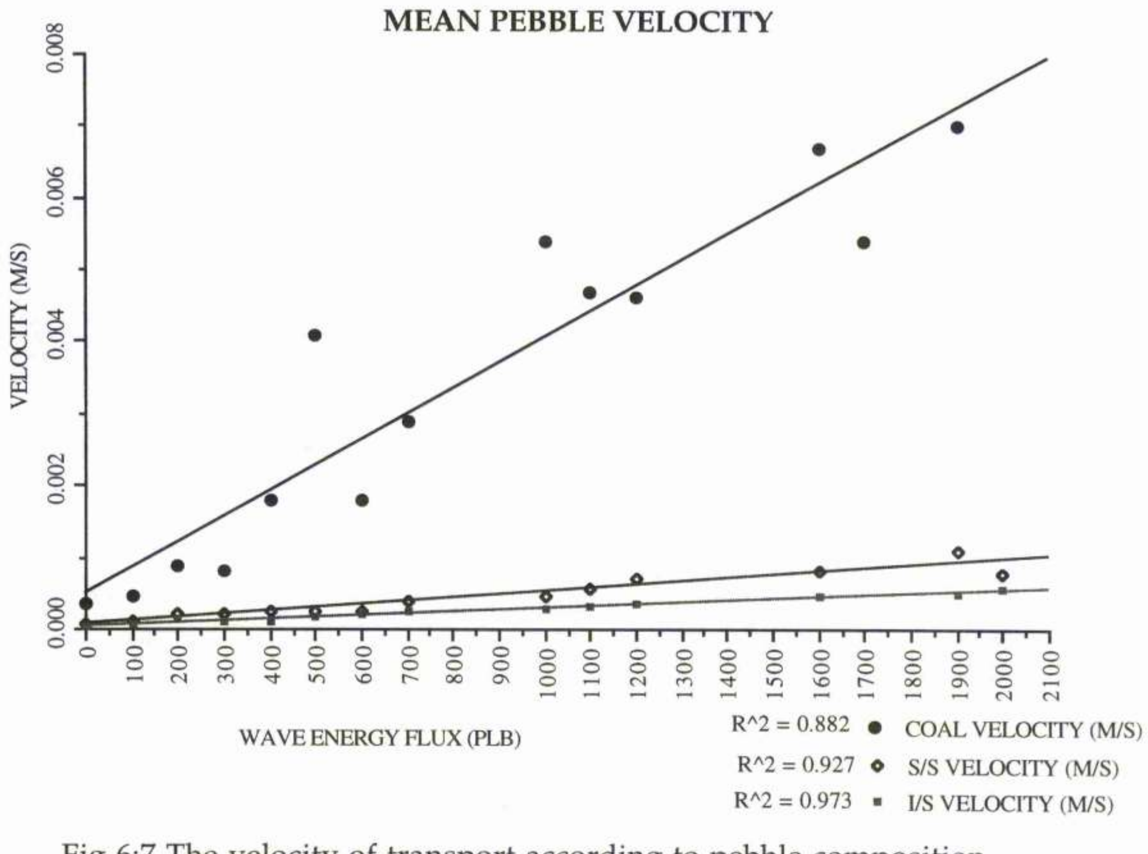


Fig 6:7 The velocity of transport according to pebble composition.

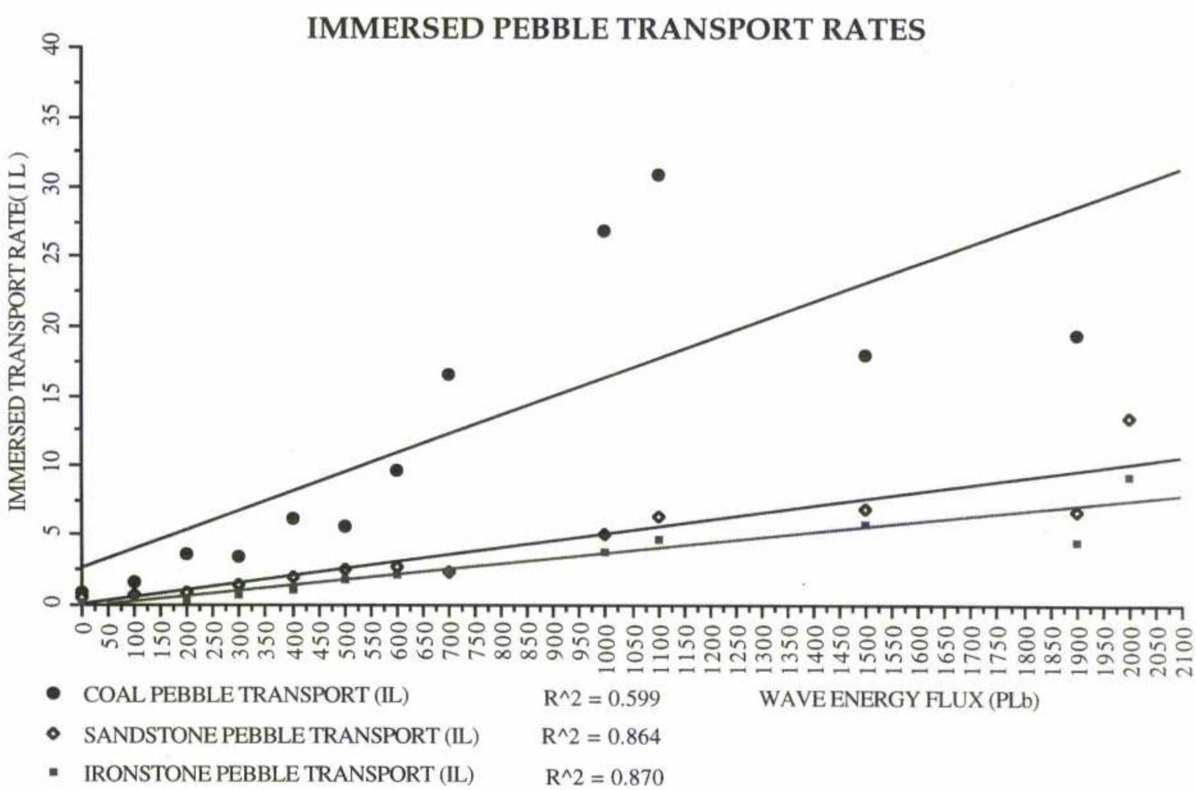


Fig 6:8 Immersed transport rates according to pebble composition.

TRACER TRANSPORT IN HIGH WAVE ENERGY CONDITIONS

In high wave energy conditions the tracer recovery rate declined rapidly following deployment (figure 6:1). The recoveries for the coal tracer pebbles were particularly poor, falling to less than 20% five tides after deployment.

COMPOSITION	WAVES SOUTHEAST SECTOR	WAVES ESE SECTOR	SOUTHWEST SECTOR
IRONSTONE	4.8m	5.2m	4.4m (- to east)
SANDSTONE	6.4 m	8.98m	5.6m (- to east)
COAL	41.5m	45m	35.3m (- to east)

Table 6:7 Mean longshore transport in one tide in high wave energy conditions.

COMPOSITION	MEANVELOCITY (M/S)	MEAN VOLUME (M/S^3)
IRONSTONE	0.00068	0.0006
SANDSTONE	0.0014	0.002
COAL	0.0072	0.004

Table 6:8 Mean velocity and volumetric transport in high wave energy conditions.

In high wave energy conditions the mean longshore transport of the ironstone tracer pebbles was approximately 4-5 metres in one tide, depending on the wave angle of approach (Table 6:7). The high energy waves were most frequently recorded from the east sectors. These waves approached at an oblique angle to the shore, therefore the longshore transport was predominately to the southwest (figure 6:33).

In high wave energy conditions a rise in the wave energy flux, the wave height and the wind speed, increased the rate of ironstone and sandstone tracer transport. The mean and maximum transport of the ironstone tracer pebbles in one tide increased significantly when the wave energy flux values rose to over 2000 (N/m/s). When waves approached from the dominant east sector, the maximum transport in one tide for the ironstone pebbles was up to 25 metres (figure 6:61). Consequently, the velocity of the ironstone pebbles was nearly twice the velocity recorded in moderate wave conditions (figure 6:7).

In high wave energy conditions the mean longshore transport of the sandstone tracer pebbles in one tide was up to 9 metres according to the wave sector (Table 6:7). The maximum transport of the sandstone tracers in one tide was approximately 30 metres, however one extreme distance of 50 metres in one tide was recorded (figure 6:62). In addition, the longshore dispersion of the sandstone tracers in one tide spanned a much wider area of the sampling grid than the ironstone tracers despite being subjected to the same wave conditions (figure 6:43a-c). The transport velocity of the sandstone tracers was 3.5 times the velocity recorded in moderate wave energy conditions, furthermore the speed of transport of the sandstone tracers increased at a steadier rate than the ironstone tracers (figure 6:7).

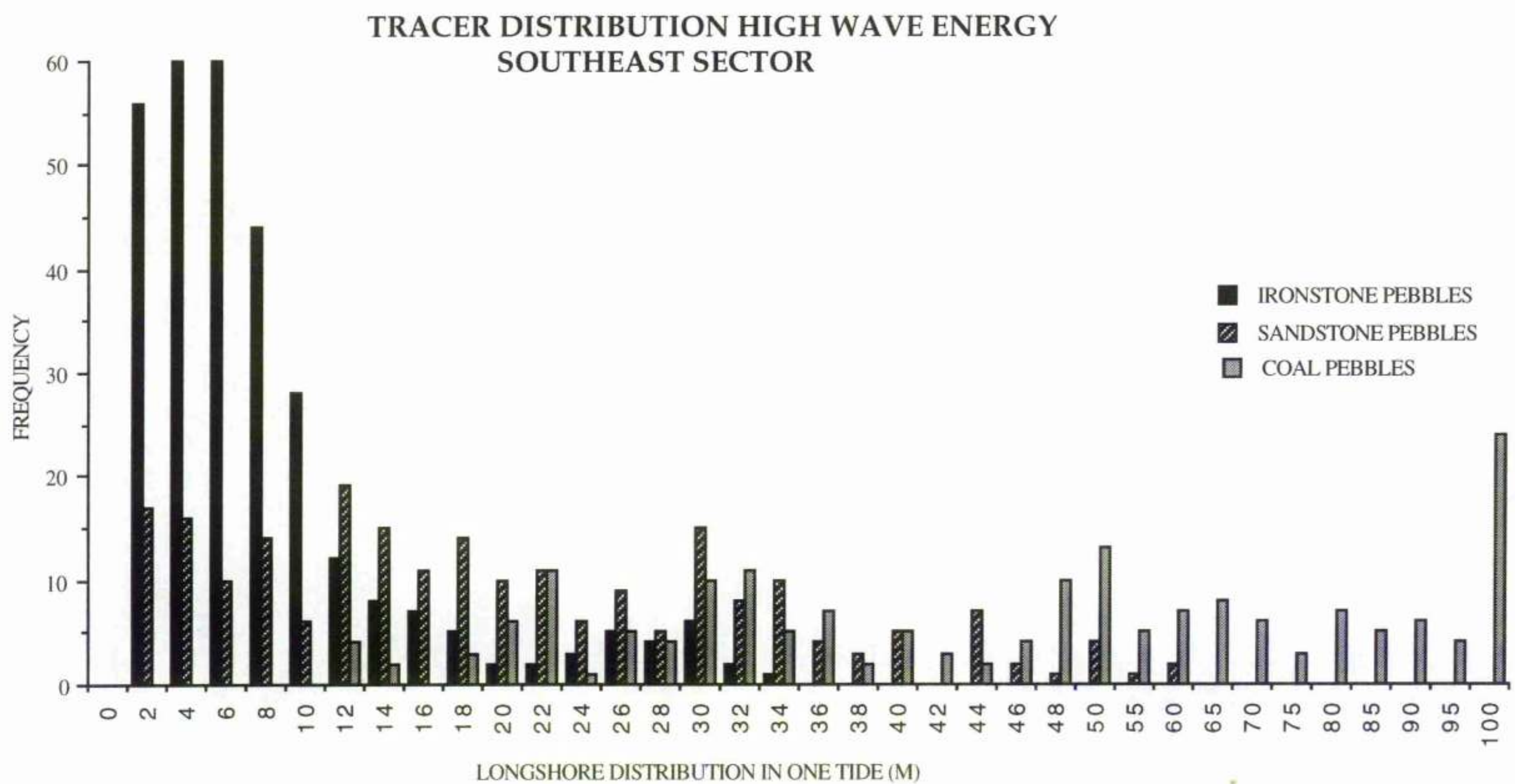


Fig 6:43a Distribution of tracers in high wave energy conditions.

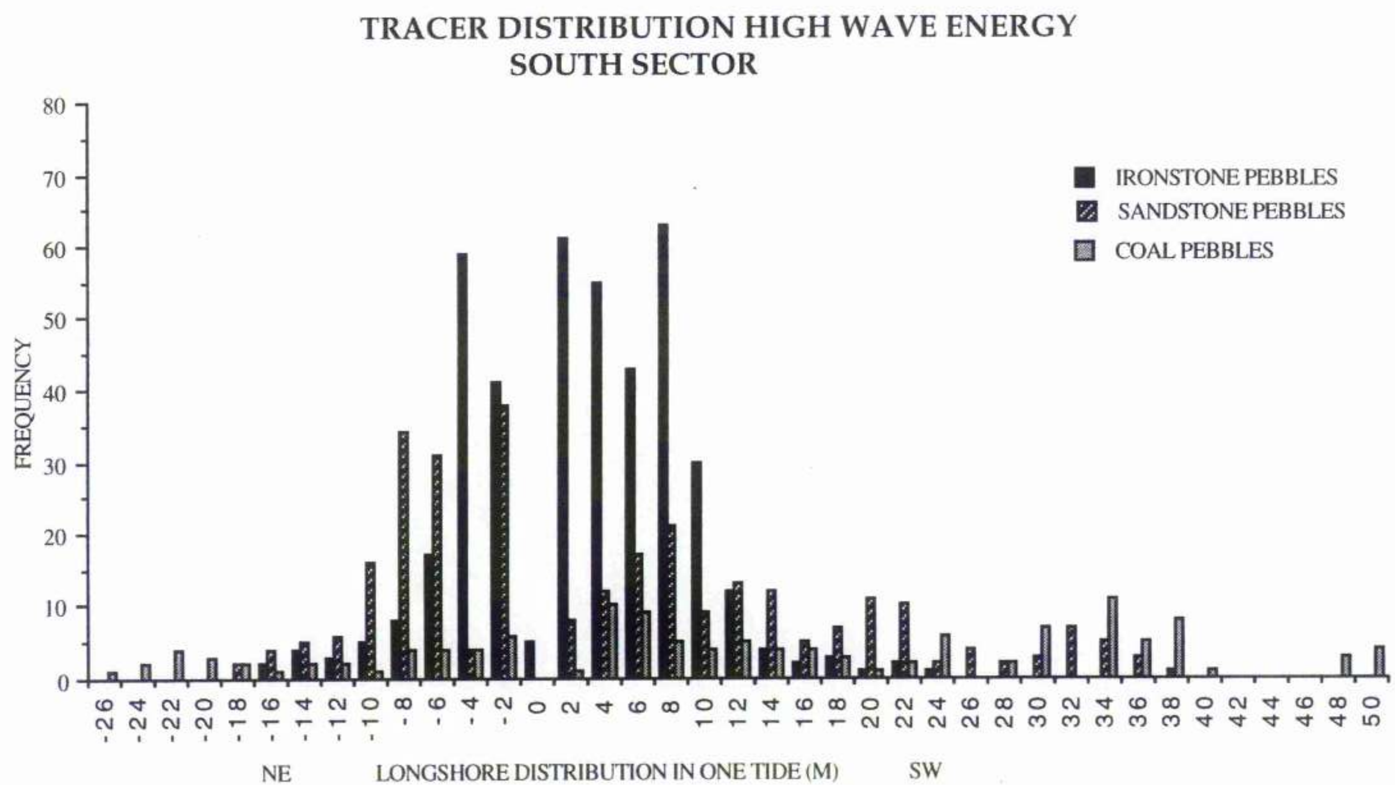


Fig 6:43b Distribution of tracers in high wave energy conditions.

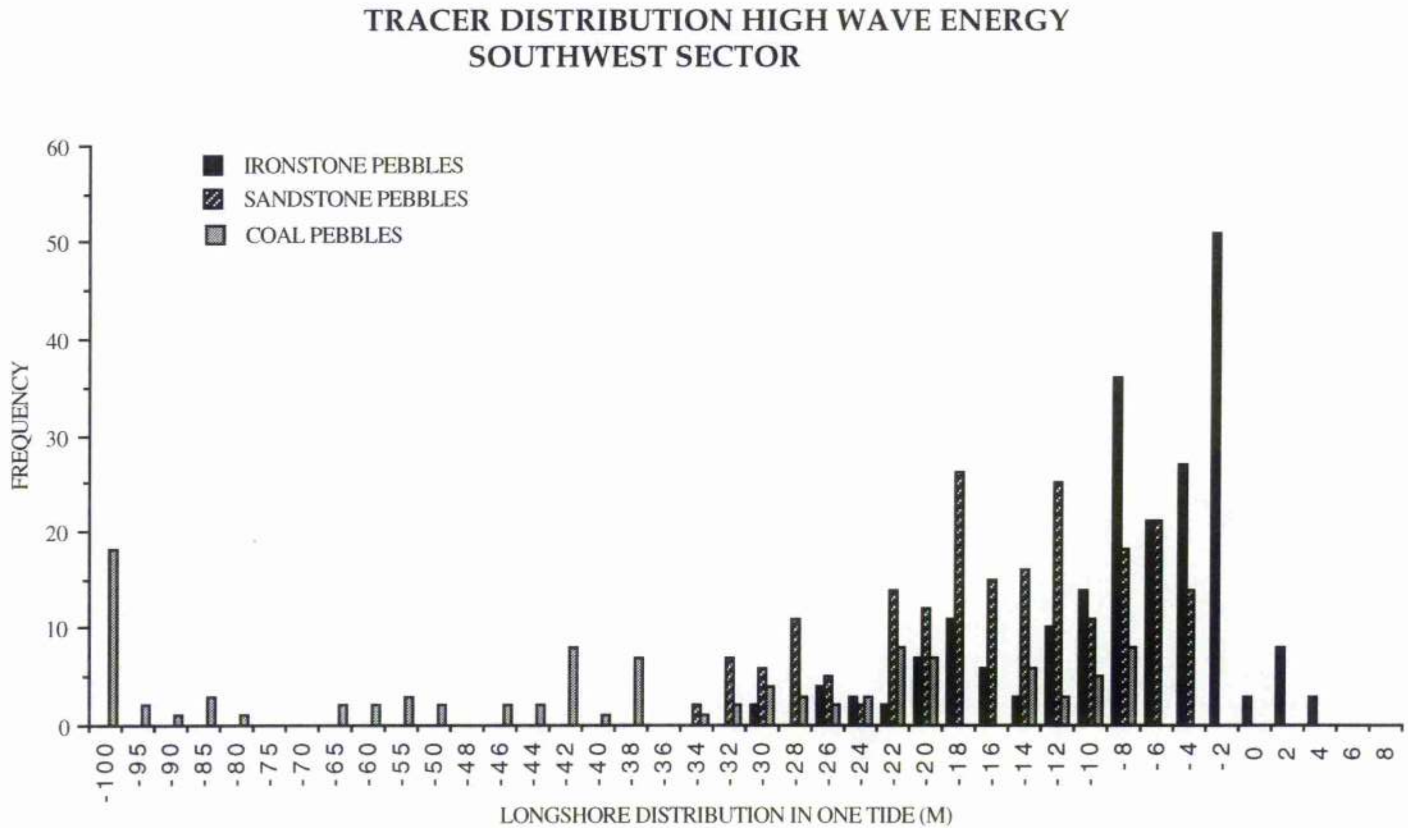


Fig 6:43c Distribution of tracers in high wave energy conditions.

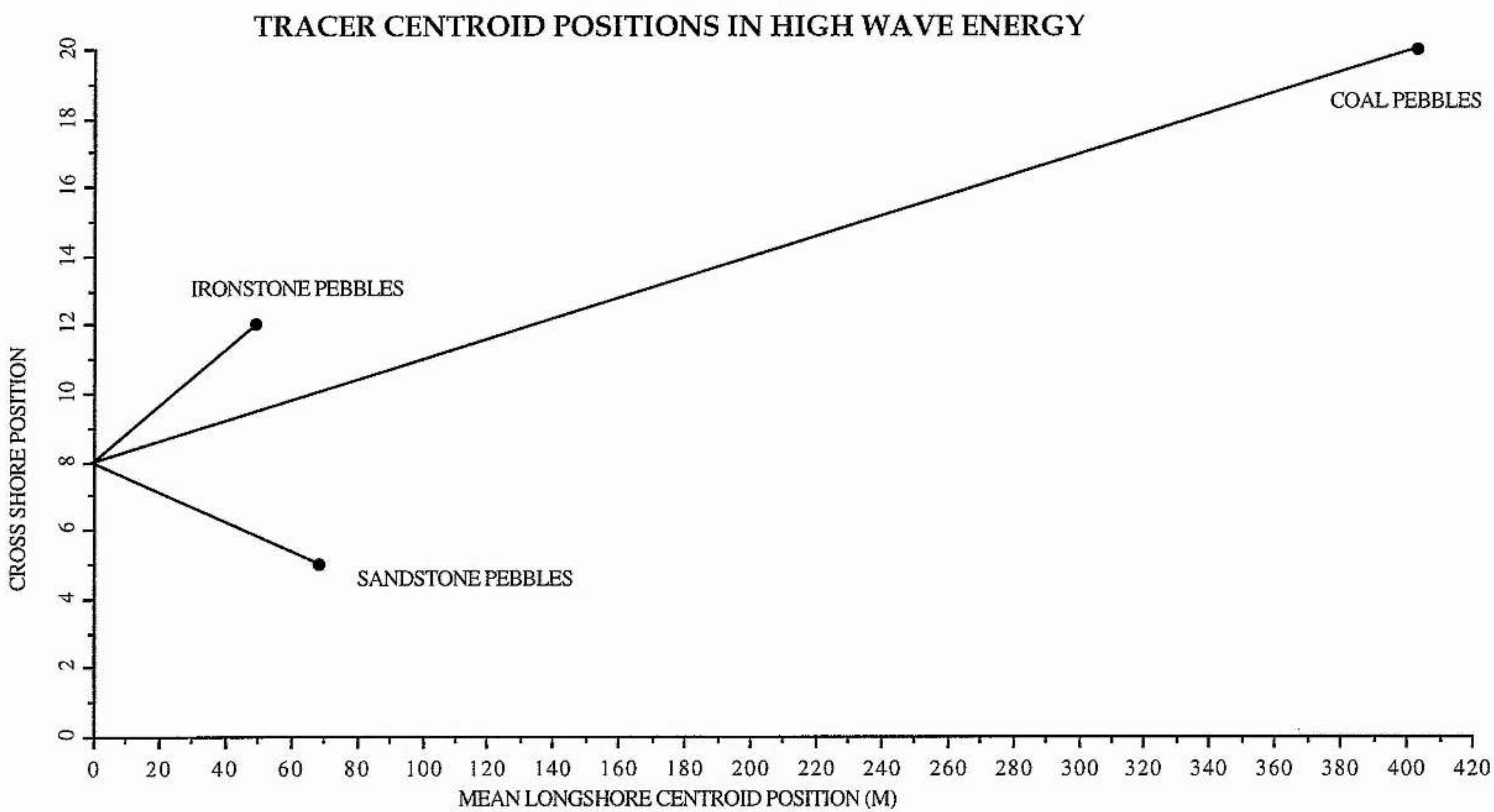


Fig 6:53 Tracer centroid displacement high wave energy

In one tide the sandstone tracers were transported up to 4 metres further than the ironstone tracers. Consequently, when high energy wave conditions prevailed for a length of time the sandstone centroid was displaced significantly further alongshore than the ironstone tracer centroid (figure 6:53).

An increase in the wave height and the wave energy flux, was responsible for the disturbance of the foreshore, therefore the volume of ironstone and sandstone tracers transported alongshore increased significantly when the wave power rose to 2000 (N/m/s) (figure 6:8). An increase in the volume of the sediment undergoing longshore transport resulted in a greater number of the tracer pebbles becoming buried, so that the recovery of the ironstone and sandstone tracers declined when high energy conditions prevailed for a significant period of time (figure 6:1).

In high wave energy conditions there was a sharp rise in the speed of transport of the coal tracer pebbles, which is indicated by the steep regression line (figure 6:7). The transport velocity of the coal tracer pebbles was up to 10 times the velocity of the ironstone tracers and approximately 8 times the velocity of the sandstone tracers (Table 6:8). In high wave energy conditions the mean longshore transport of the coal tracers in one tide was between 30-40 metres, however a significant proportion of the coal tracers was transported to distances over 100 metres in one tide (figure 6:43a-c). The dispersion of the coal tracer pebbles in one tide was highly variable, despite the tracers being similar in size. Therefore, the correlations of coal tracer transport with increasing wave flux and wind speed are poor, with regression values of only R^2 0.59 and R^2 0.35 respectively (figure 6:63/6:2). When the wave power was over 2000 (N/m/s) all the coal tracers were lost (figure 6:63). It was assumed that the coal tracers were transported beyond the limits of the survey grid and offshore by waves and currents.

6:12 DISCUSSION ON THE RESPONSE OF PEBBLES IN WAVE ACTION

The tracer surveys illustrated that the wave angle had a very significant control on the rate and direction of longshore transport of the tracer pebbles in all wave energy conditions. The dominant southeast waves arrived at an oblique angle and dissipated a higher proportion of wave power alongshore, therefore the net longshore transport was to the southwest. The net sediment transport was not entirely unidirectional, because locally generated wind waves from the southwest reworked the pebbles to the northeast. The wave power of the southwest waves was less than the dominant southeast waves, however the southwest waves have a higher annual frequency of occurrence than the southeast waves. Therefore, this counterdrift transport to the northeast was particularly significant in maintaining the stability of the beach. Waves from the south sector were restricted in height and fetch due to local topographic effects. These waves approached normal to the shoreline, wave energy reflected from the foreshore induced currents that transported the tracers in both directions.

The locally generated wind waves had variable heights and wave periods and when they interacted with the dominant southeast waves an even more complex pattern of waves and sediment transport was created.

The weekly net pebble transport was calculated for the summer period (Table 6:9). A previous investigation by HR Wallingford (1994) predicted a volumetric transport rate of 75,000m^3 per annum. However, these weekly calculations do not take into account the winter period when the transport rates are more significant, as the wind and wave activity is greater.

PEBBLE COMPOSITION	VOLUMETRIC TRANSPORT (M^3/WEEK)
COAL	1,856
SANDSTONE	305
IRONSTONE	174

Table 6:9 Weekly mean transport to the southwest in moderate conditions.

The table highlights that the volumetric coal pebble transport will overestimate the longshore transport of the mixed beach sediment. Whereas, transport predictions based on the dense ironstone pebbles underestimated the pebble transport on the mixed beach. For accurate predictions of sediment transport on heterogeneous pebble beaches, the composition must be taken into account. In addition to the role of pebble composition in wave action, there were other factors that influenced pebble tracer transport, these factors are discussed below.

6:13 WIND EFFECTS ON PEBBLE TRACER TRANSPORT

Although there was a clear correlation between the mean transport in one tide and the wind speed, the tracer results did not take into account the duration of the winds. When the winds blew for a longer duration in the same direction and when the wind and wave angles of approach coincided, the tracer transport rates increased.

Northeast and northwest winds blew off the land and opposed the direction of wave advance, therefore tracer transported were reduced. Swell waves in storm recovery stages also gave rise to anomalies in the tracer data. The wave generating winds had ceased, however the swell waves possessed high energy and the tracers were transported further than expected.

It was observed that the wind direction and velocity changed more readily than the wave angle. In the summer, sea breezes reversed the wind direction and increased the wind speed in the afternoon. These wind reversal patterns were short lived and opposed the wave angle of approach. In addition, locally generated winds frequently blew in opposition to the dominant southeast waves. Light density coal tracers were transported alongshore in a direction that opposed the transport direction of the ironstone and sandstone tracers. Observations of the coal tracers in transport highlighted that coal pebbles of particularly low density were transported in suspension and supported in the upper water column by wind drift effects on the upper part of the waves. Whereas, the sandstone and ironstone tracers were transported as bedload in the lower water column according to the wave angle of approach which opposed the wind direction.

6:14 CROSS SHORE PEBBLE TRANSPORT

Superimposed on the wave induced longshore transport was a cross shore transport of the tracers. Changes in the beach micro-topography and the high water mark were monitored in conjunction with the cross shore (X) vectors of tracer transport (figure 6:11). A systematic cross shore transport of the tracers was identified as the tidal range changed from high Spring tide levels to low Neap tide levels.

As Spring tides were approached, the high tide level progressively increased from 4.5 to 5.8 metres and the tracers displayed a significant upshore transport (figure 6:9). The accretion of pebbles took place at swash berms and the coded sandstone and ironstone tracer pebbles revealed that tracers previously buried in the swash berms were reworked upshore as the high tide level rose (figure 6:11B). When the tide level was at 5.0 metres the sandstone tracer pebbles had a mean upshore movement of 2 metres in one tide. The mean transport upshore, increased to a maximum of 4 metres when the high tide level reached 5.8. (figure 6:9a-c). An increase in the water depth resulted in a higher proportion of wave energy being dissipated on the foreshore. With an increase in the tide height, the mean upshore transport of the ironstone tracer pebbles increased from 0.5 metres to 1.5 metres. The correlation of the transport upshore of the ironstone and sandstone pebble tracers with an increase in tide level, had a regression value over R^2 0.9. Whereas, the coal tracer pebbles had a poor relationship between upshore transport with rising tide level (figure 6:9a-c).

The upshore transport of the tracers was also dependent on the wave angle. When the waves corresponded to the south sector, wave energy was dissipated normal to the shore and increased the transport of the tracers upshore (figure 6:9b).

As neap tides were approached the high tide level fell from 5.4 to 4.1 metres. The tracer pebbles were reworked to the lower foreshore (figure 6:10a-c). The coal tracer pebbles were transported up to 11 metres down shore in one tide. This down shore transport in one tide decreased as the high tide level fell to 4.1 metres. The recoveries of the coal tracer pebbles on the lower foreshore were low, as there was insufficient time for the light density coal pebbles to settle out of the water before the next incoming swash. With falling high tide level, coal tracers of particularly low density were stranded at the maximum swash limit.

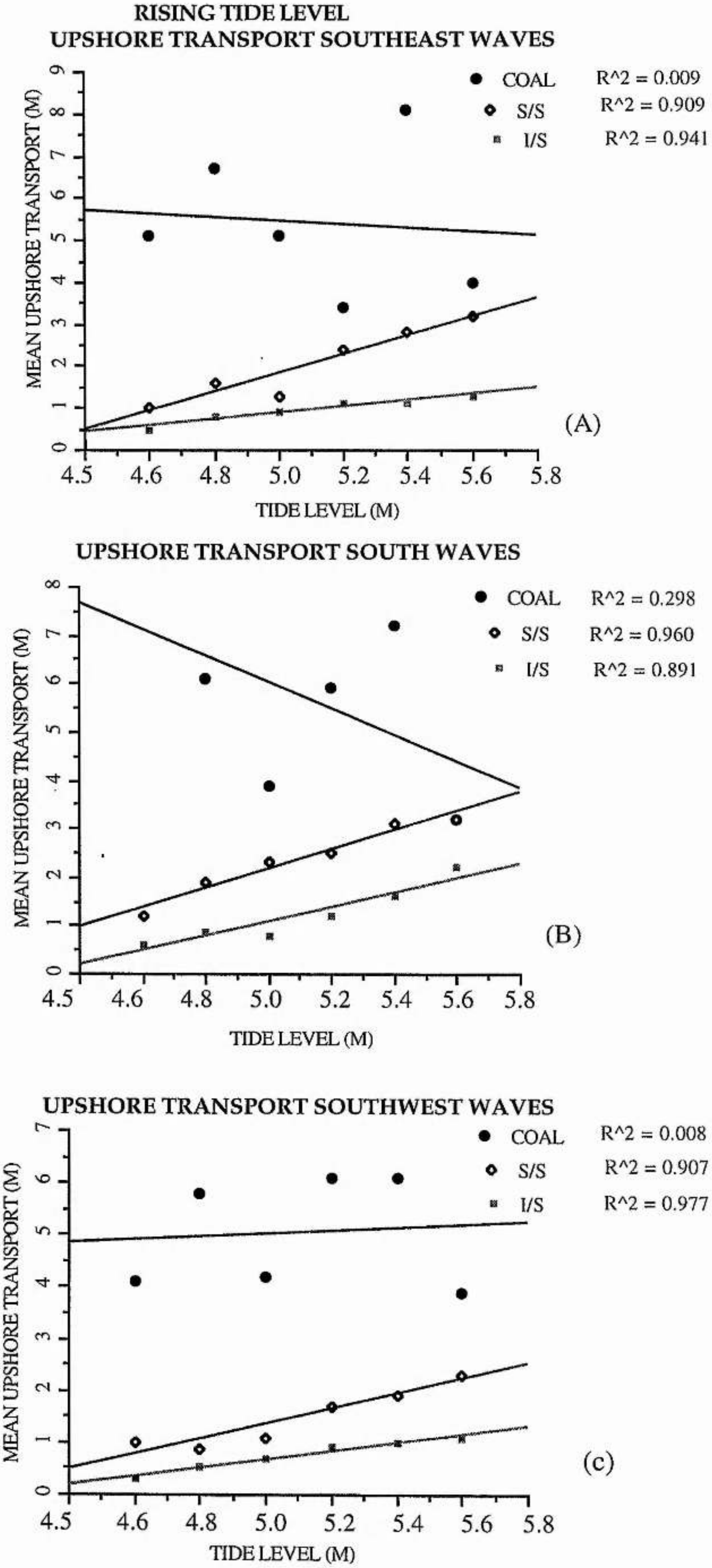


Fig 6:9 Cross shore transport Rising Tide level.

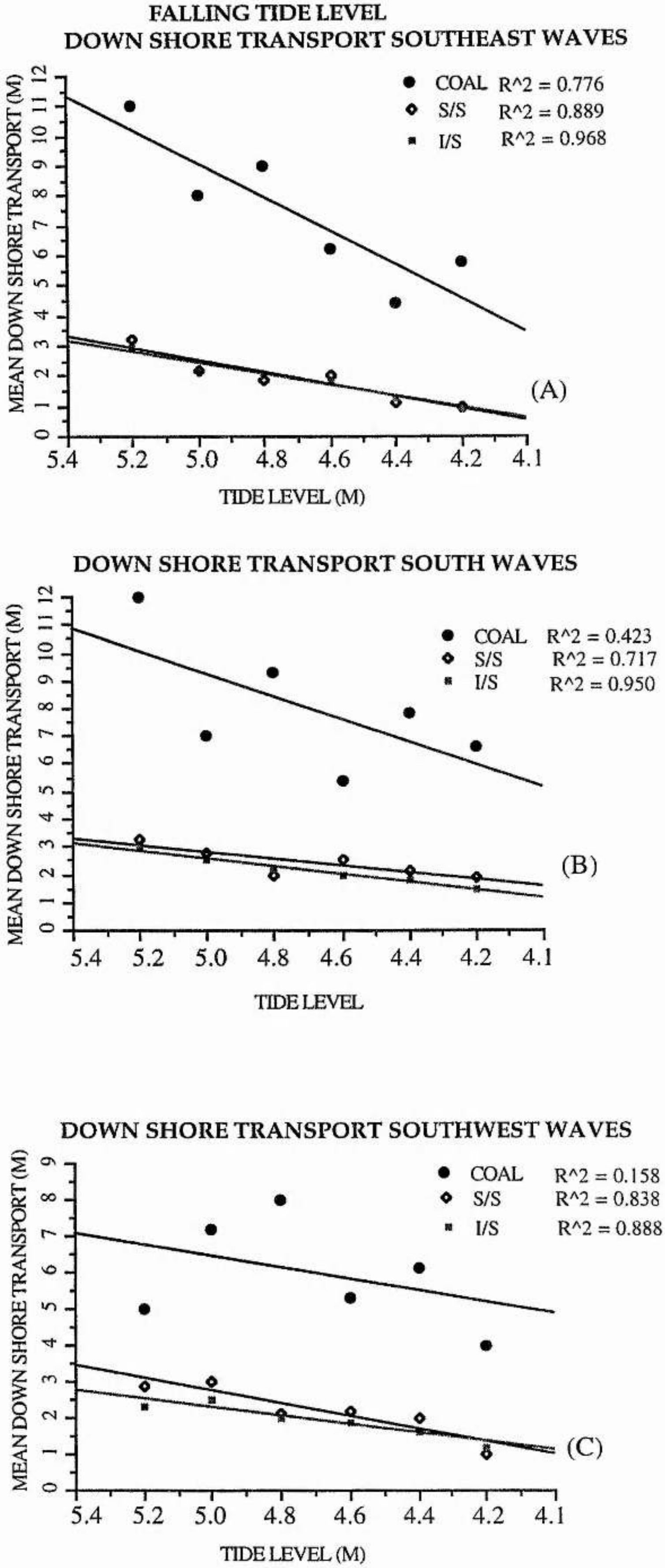


Fig 6:10 Cross shore transport Falling Tide Level.

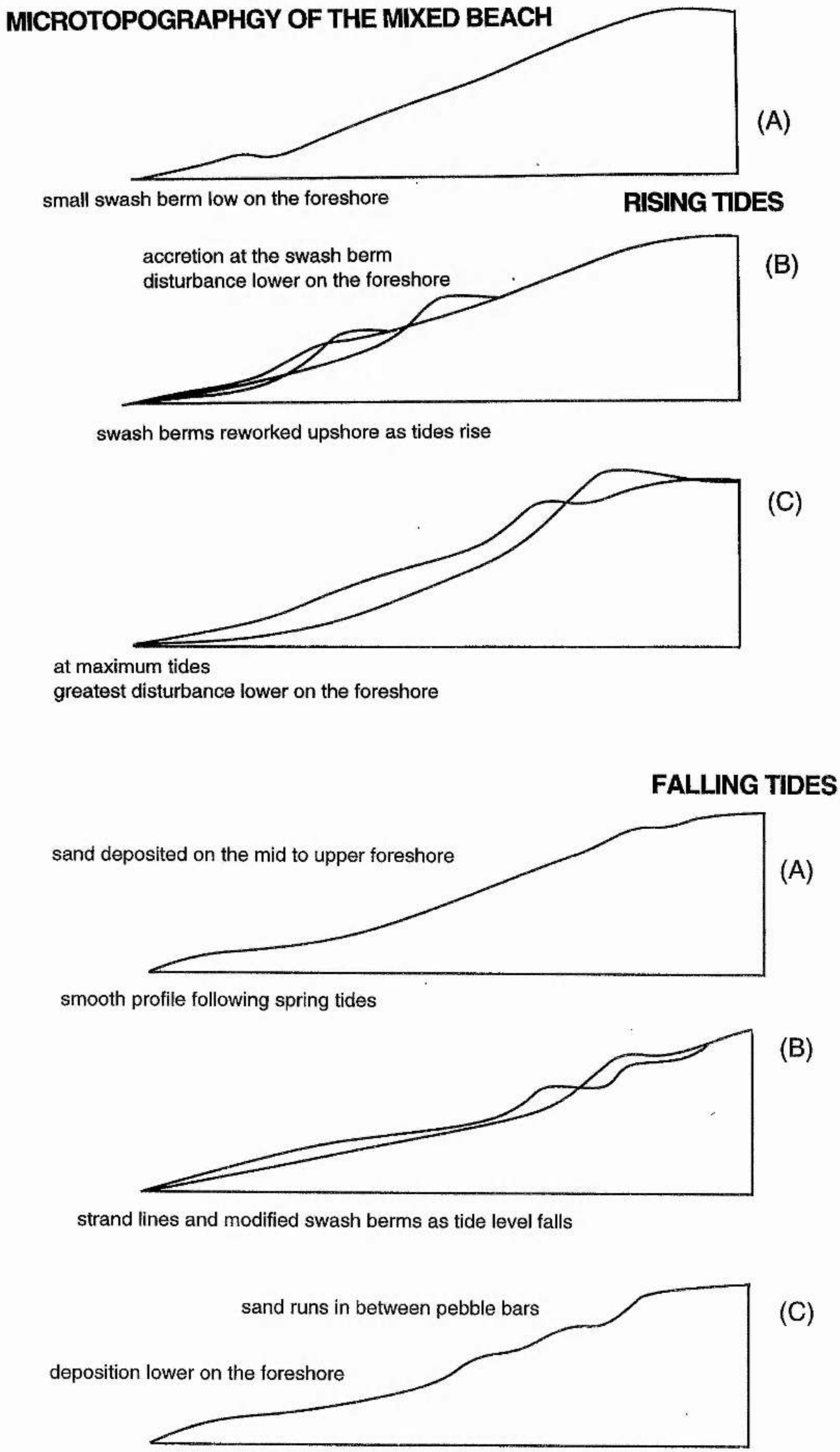


Fig 6:11 Profiles -Tidal sequence.

As the high tide level fell, the mean transport down shore for the ironstone and sandstone tracer pebbles was similar. The mean transport rate decreased from 3 metres to 1 metre in one tide (figure 6:11C). Observations revealed that the high density of the ironstone tracers increased the inertial properties of the pebbles and thus, enhanced rolling down the gradient of the beach slope, that varied between 8-12 degrees. This accounted for why the cross shore transport of the ironstone pebbles frequently exceeded the longshore transport of the ironstone.

Although, the tide level significantly influenced the transport of the tracer pebbles in low to moderate wave energy conditions, with an increase in the wave angle and the wave height the wave induced transport became more important.

6:15 THE INTERACTION OF PEBBLE SHAPE AND COMPOSITION IN WAVE ACTION

The interaction of pebble shape and composition in wave action was examined in two tracer surveys. The mean longshore transport in one tide was established for disc, rod, blade and sphere shaped pebbles composed of ironstone, sandstone and coal. The interaction of pebble shape and composition was correlated to the wave height, that was taken as a measure of the wave energy.

A comparison of coal pebbles of different shape in wave action revealed that at wave heights below 0.35 metres the coal tracer pebbles moved irrespective of shape (figures 6:12/6:13). As wave heights increased to 0.60 metres the disc shaped coal pebbles were transported up to 2 metres further than the rod and sphere shaped pebbles of similar size and composition (figure 6:16). The other coal pebbles displayed no specific trends according to shape.

The interaction of sandstone and shape in wave action was more significant (figure 6:12/6:13). Two contrasting trends of transport according to pebble shape were identified. The rod and sphere shaped sandstone pebbles had similar transport behaviour and contrasted to the behaviour of the blade and disc shaped sandstone pebbles. The longshore transport of the rod and sphere shaped sandstone pebbles increased linearly as the wave height increased (figure 6:15). At low wave heights the sphere and rod shaped sandstone pebbles moved approximately 2-3 metres in one tide (figure 6:12), whereas the rate of transport for the disc and blade shaped pebbles was only between 1.5 and 2 metres in one tide (figure 6:13). The difference in transport rate between the two contrasting groups of pebble shapes declined as the wave heights increased. At wave heights over 0.40 metres, the disc and blade shaped sandstone pebbles moved further alongshore in one tide than the rod and sphere shaped pebbles. With a rise in the wave height, the speed of transport of the blade and disc shaped sandstone pebbles increased at a faster rate than the rod and sphere shaped sandstone pebbles (figure 6:15). For wave heights over 0.50 metres disc and blade shaped pebbles moved 2 metres further in one tide, than the rod and sphere

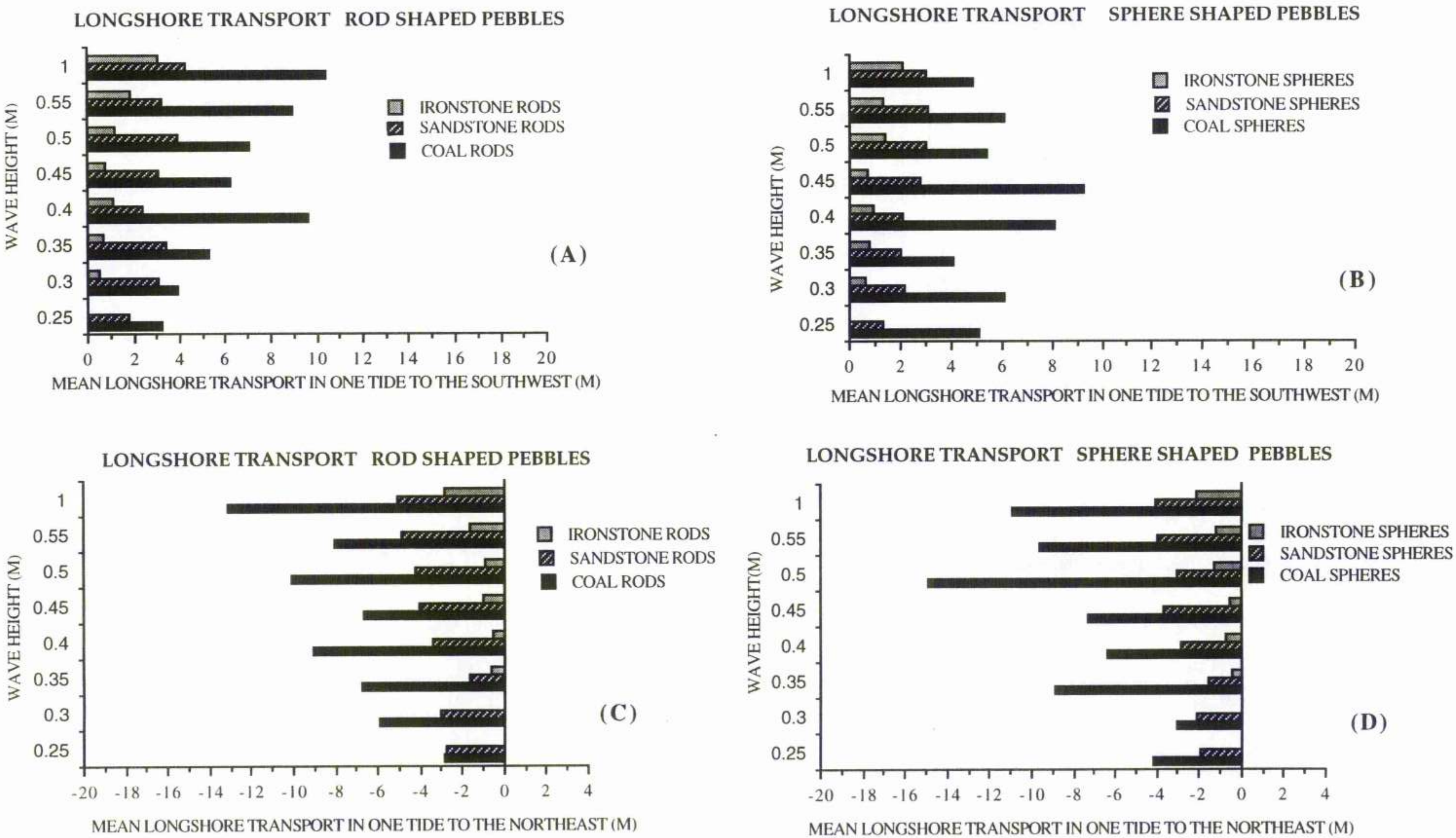


Fig 6:12 Transport of rod and sphere shaped pebbles.

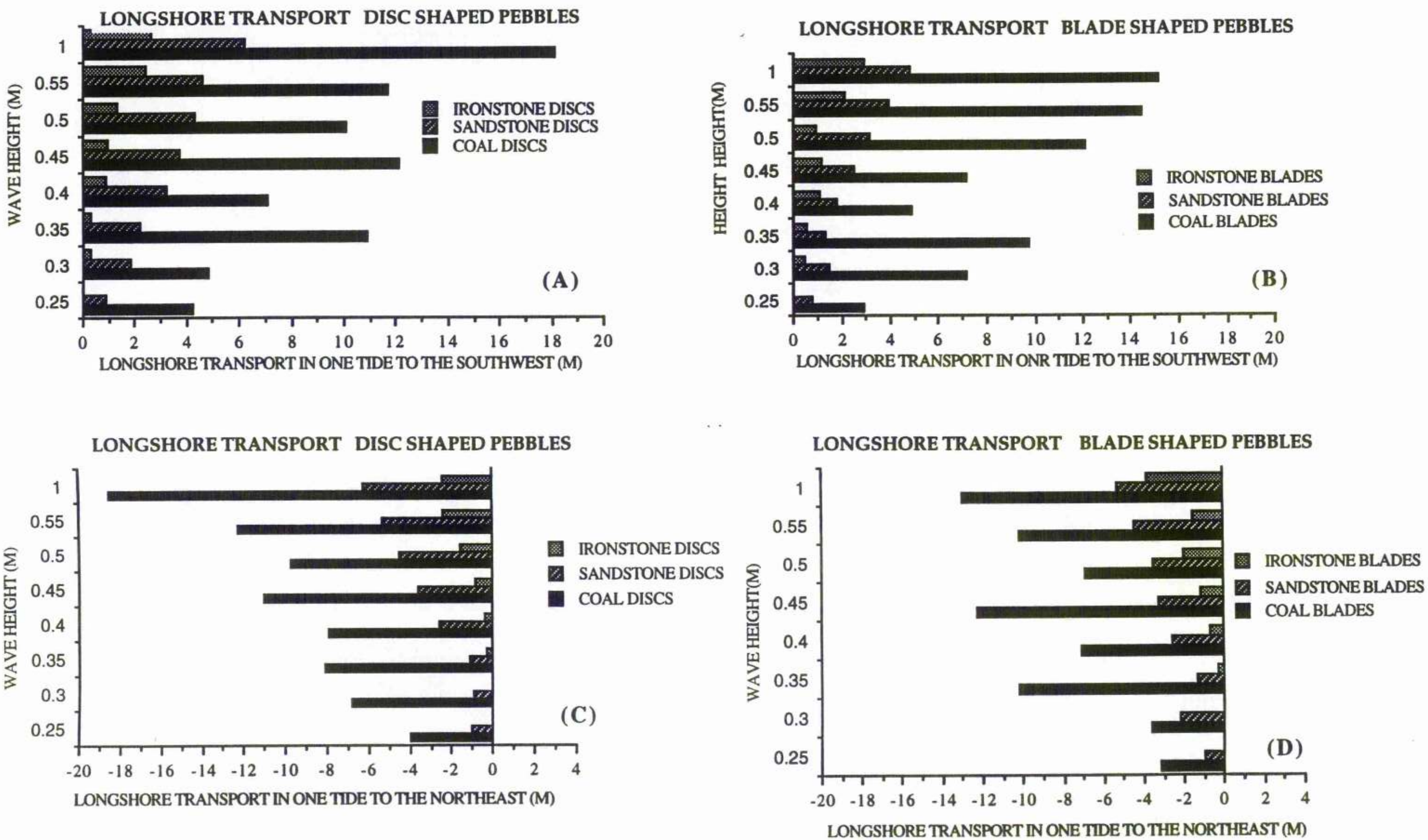
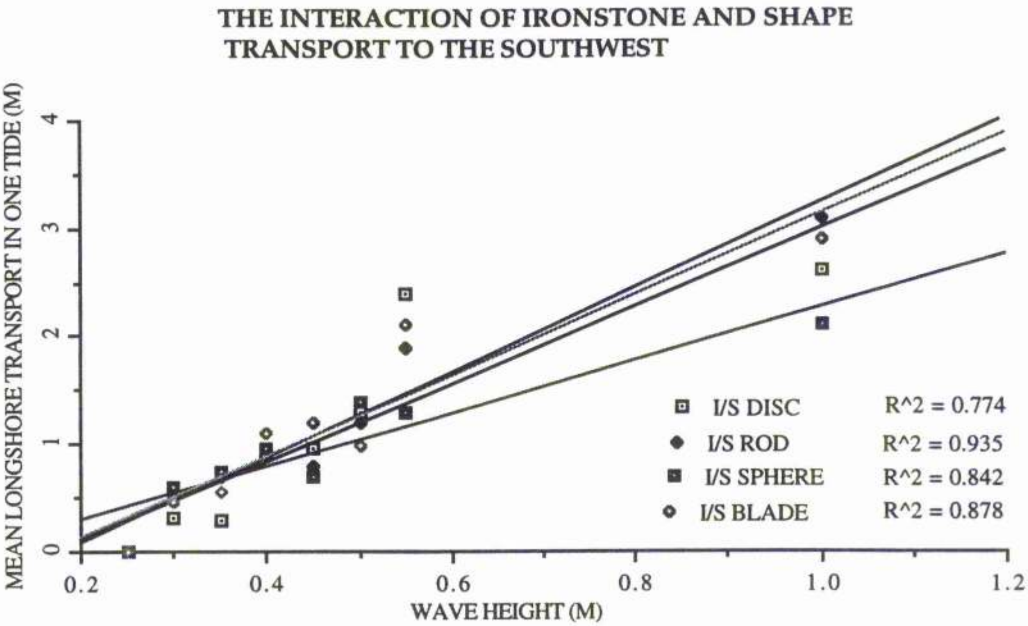


Fig 6:13 Transport of disc and blade shaped pebbles.

shaped sandstone pebbles. At wave heights over 0.80 metres, the disc shaped sandstone pebbles were transported 2-3 metres further in one tide, than the other three pebble shapes. The response of pebble shape in wave action had similar trends for waves from the southeast and the southwest sectors.

There was no transport of the ironstone pebbles until the wave heights reached 0.30 metres. With an increase in the wave height the longshore transport in one tide increased linearly for all pebble shapes (figure 6:14). Although the ironstone pebbles shared certain similarities in the shape behaviour with the sandstone pebbles, the shape selection process was less consistent.

In conclusion, the influence of pebble shape on transport rates was dependent on the composition of the pebble. Shape selection in wave action influenced the transport behaviour of the sandstone pebbles and was dependent on wave energy. In low wave energy, sphere and rod shaped sandstone pebbles were transported further alongshore than the disc and blade shaped pebbles that required a higher wave energy threshold for initiating transport. As the wave height increased it is speculated that the disc shaped pebbles were carried in suspension or they slid over the other shapes in motion in the direction of wave propagation, whereas the rods and sphere shaped pebbles rolled to and fro, in the swash and backwash. In contrast, the density of the ironstone and coal pebbles was the physical parameter controlling transport. Through the use of tracers, it was identified that on the heterogeneous mixed beach, the composition of the pebbles significantly controlled both the rate and direction of transport.



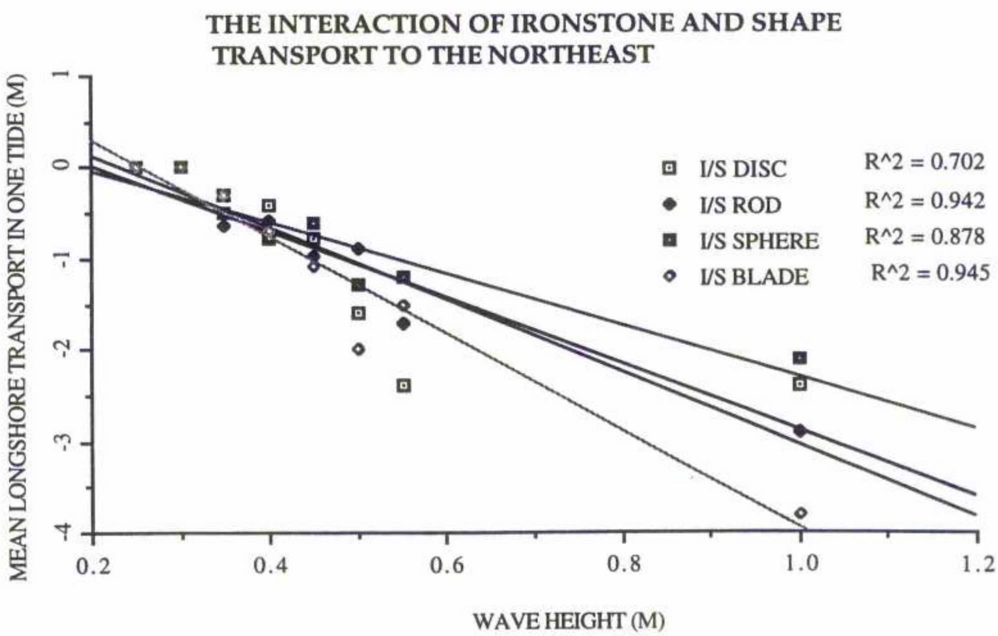
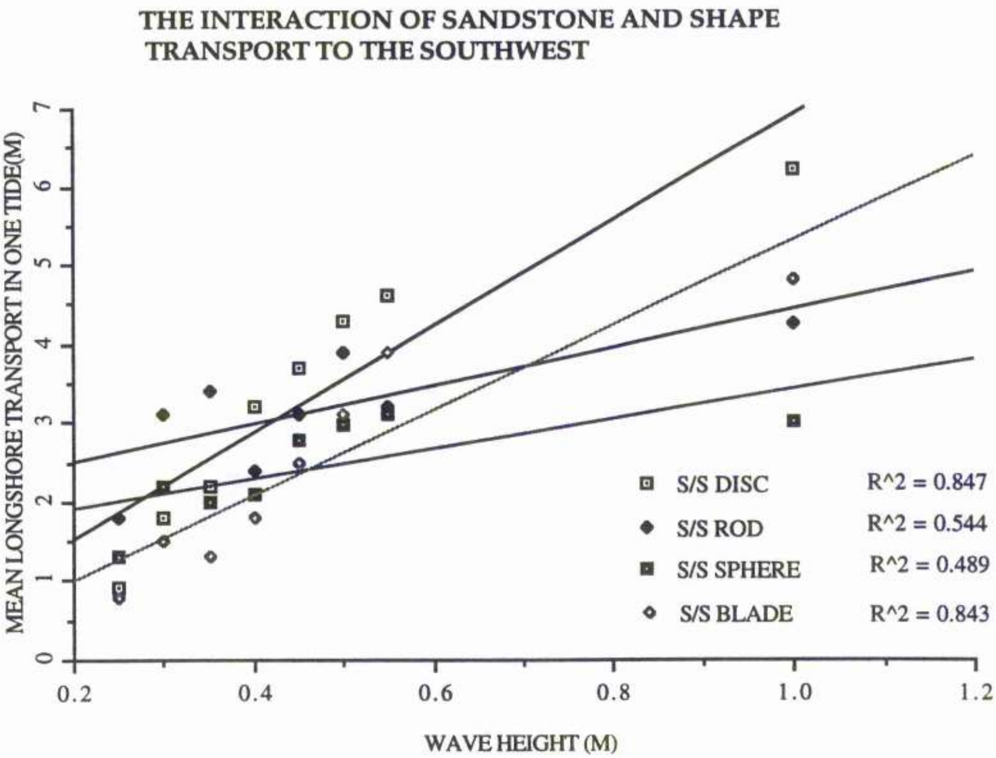


Fig 6:14 Correlation of ironstone shape and transport.



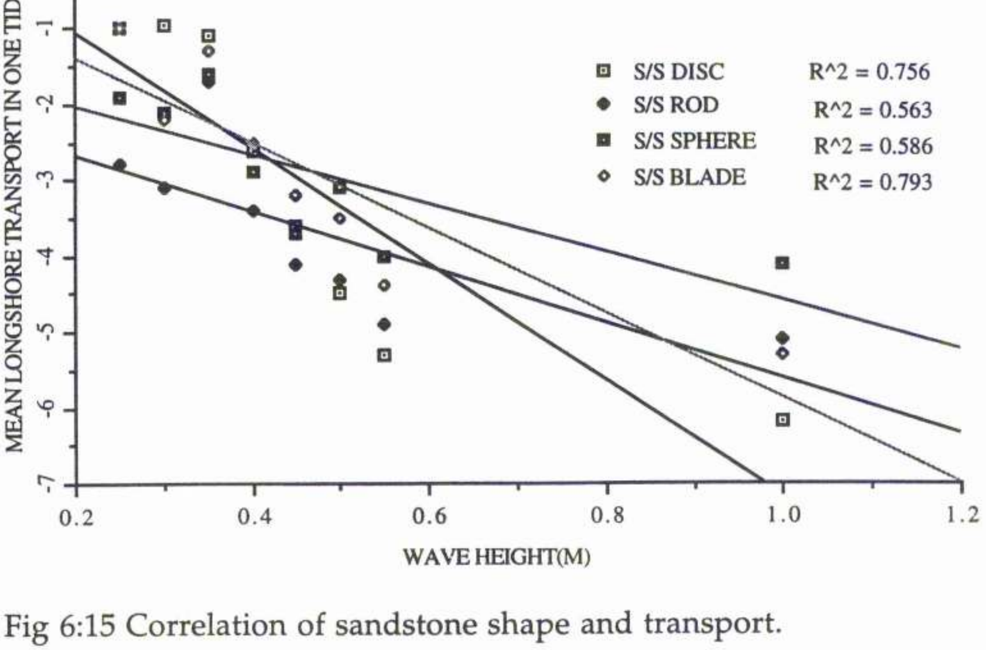
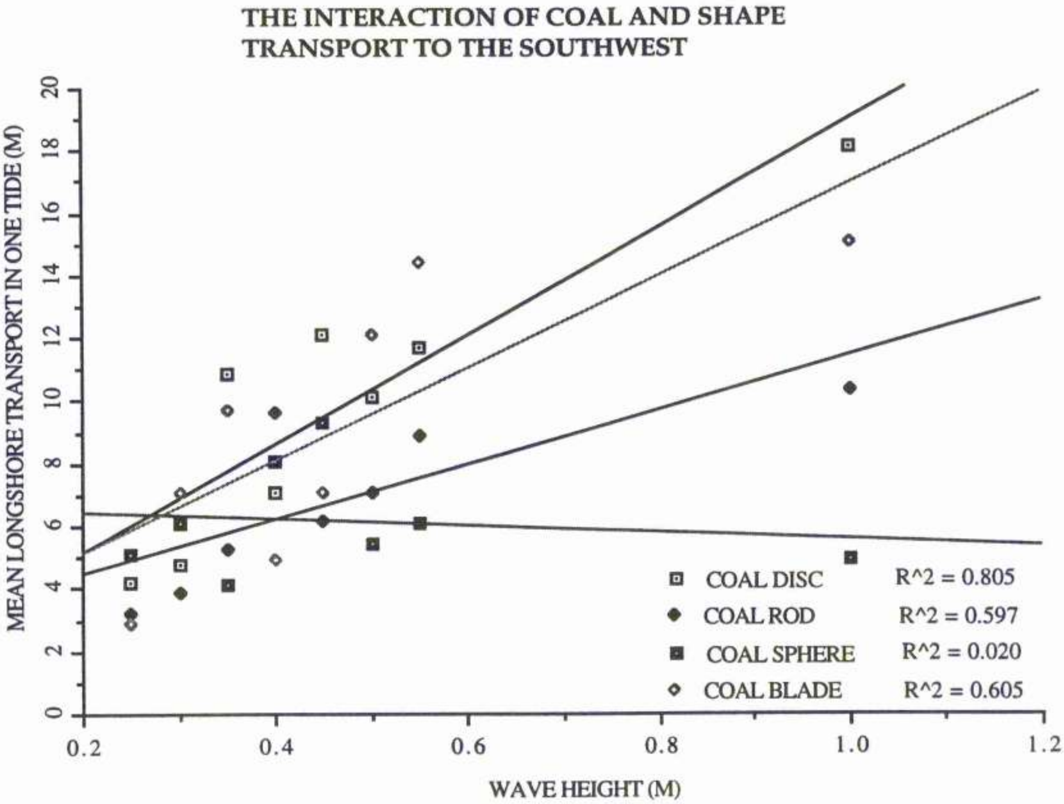


Fig 6:15 Correlation of sandstone shape and transport.



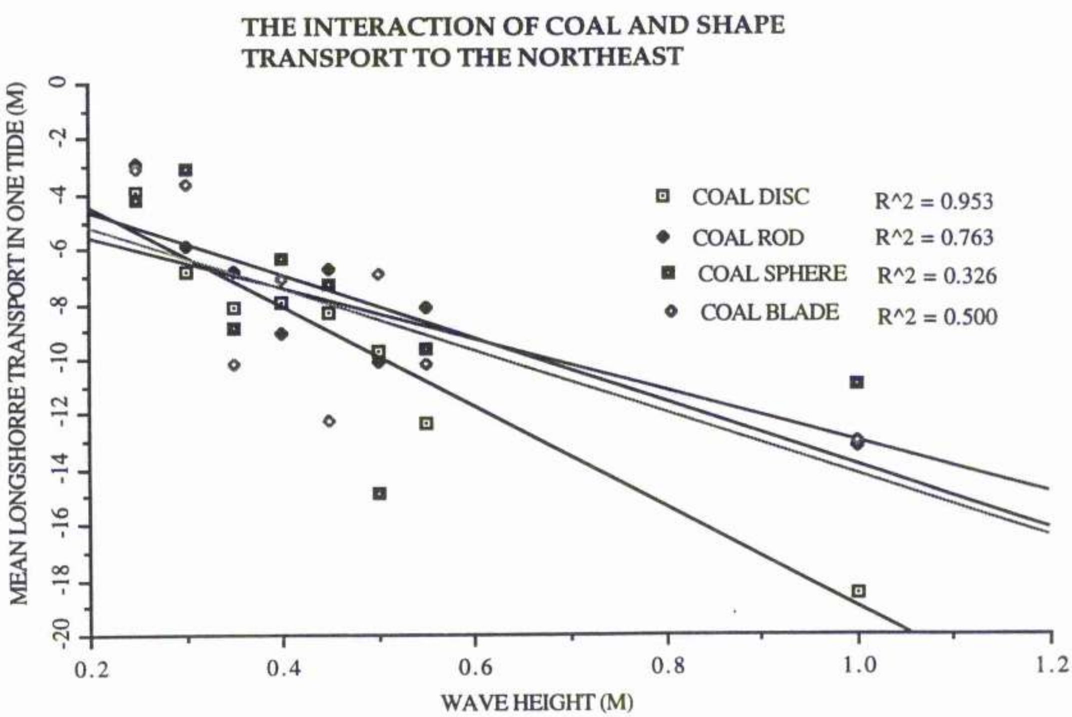


Fig 6:16 Correlation of coal shape and transport.

7:1 INTRODUCTION DEPTH OF DISTURBANCE ON BEACHES

The disturbance of a beach face as a result of the shear stress exerted by wave, tide and current action mobilises the upper layer of sediment to a certain depth enabling the sediment to move laterally and vertically. Therefore, the depth to which a beach face is disturbed relates to the thickness of the laterally moving layer of beach sediment undergoing longshore transport (Kraus 1985).

King (1951) pioneered the technique for determining the thickness of the moving sediment layer on sand beaches. Vertical cores were excavated in the beach face and infilled with coloured tracer sand. After wave action has disturbed the beach face, the thickness of the length of the remaining tracer sand in the core was measured. As the initial length of the core was known, a time averaged maximum thickness of the mobile sediment layer could be established for each tide. King (1951) inferred that a rise in the wave height induced greater disturbance of the beach face, as the turbulence of the breaking waves increased the shear stress exerted on the bed. She showed that the depth of disturbance on a sand beach increased by 1 cm for each 30 cm rise in wave height. This linear correlation was found up to wave heights of 1.5 metres, thereafter the rate of increase in the depth of disturbance decreased. This was attributed to the fact that the bottom shear stress becomes less as the wave height increased, because the friction and turbulence decrease.

To increase the accuracy of calculating the thickness of the moving sand layer, the vertical sand cores were divided into segments, to investigate the transport rate at various depths. After wave action had disturbed the beach face the concentration of the tracer sand in each of the vertical core segments were examined. The maximum rate of transport of the moving sediment layer was at the beach surface and the rate of transport declined sequentially with depth (Crickmore 1962).

$$Z\,n = h \frac{\sum_{k} N\,k}{N\,max} \qquad \text{(Equation 7:1)}$$

$Z\,n$ a descriptive subscript denoted to the mixing depth
$N\,k$ tracer sand concentration within a particular segment
N_{max} maximum concentration in any segment of the core
h core segment length

Madsen (1974) argued that the concentration of the tracer sand with depth in the vertical core was not a true reflection of the thickness of the moving sediment layer undergoing transport. The regular distribution of the tracer sand in the upper sand core was assumed to represent the mixing and transport of sand within the moving sediment layer. Whereas, the irregular sand tracer distribution at depth was associated with vibration induced by wave breaking. This enabled the vertical mixing of sediment to take place without transport. Consequently, the change in the gradient in the core was assumed to be a more efficient method of identifying the thickness of the moving layer of sand on beaches.

An alternative hypothesis proposed by Kraus (1985) was that the upper part of the tracer sand core underwent mixing and transport in average wave conditions, whereas at depth mixing and transport of sand occurred in extreme events. Lee (1995) argued the inverse, that extreme wave conditions result in intermittent transport whereas, in less extreme conditions the sand was assumed to be lifted around the intermittently transported sand to greater depths.

The various approaches taken to establish the depth of disturbance on sand beaches highlight that there were numerous wave factors which caused sediment activation and the disturbance of the beach face. It was agreed among researchers that the mean depth of disturbance on sand beaches was less than 5 cm in moderate wave energy conditions.

The literature on the depth of disturbance on shingle beaches is limited, as investigating the disturbance of loosely consolidated, porous shingle is more problematic. One method used to investigate the depth of disturbance on a shingle beach involved the deployment of pebble tracers. It was assumed that the maximum depth to which the pebble tracers were recovered from beneath the beach face over the complete longshore tracer spread represented the thickness of the pebble layer in motion. However, a review by Bray (1990) highlighted that the maximum depth to which the tracers were recovered may represent an extreme event, not the thickness of the sediment in motion. Furthermore, if a large number of tracers lie on the beach surface the thickness of the transported layer would be underestimated, conversely if a large number of tracers become deeply buried the thickness of sediment in motion would be overestimated.

A more accurate method of calculating the thickness of the moving sediment layer on a pebble beach involves inserting vertical cores made up of fluorescent pebbles of similar diameter into the beach face. The pebbles are numbered with respect to the beach surface then inserted into the core in the correct order. After the pebble core is dispersed by the waves the maximum depth of disturbance of the pebble beach can be established from the number of the upper most pebble found in situ. Alternatively, vertical pebble cores have been made up of artificial pebbles which reproduce the physical characteristics of the indigenous pebbles. After the beach face was disturbed, the aluminium pebbles in the vertical cores were recovered with a metal detector Nicholls (1985 and 1989) Bray et al. (1995). Care is needed when using artificial pebble cores because if the segments are too small the pebble core breaks due to processes other than sediment transport.

The depth of disturbance recorded on pebble beaches was three times the thickness of the disturbance on a sand beaches under similar conditions. Bray (1993) found that in moderate wave energy conditions for pebble beaches along the South Dorset Coast, the disturbance varied between 8-18 cm, with a mean disturbance of 12.5 cm. This was similar to the thickness recorded on Hurst Spit beach by Nicholls (1985). The disturbance represented a moving sediment layer which was a few pebble diameters thick. In contrast to sand beaches, pebbles allow water to percolate more quickly through the beach face which aids disturbance. Furthermore, coarse pebbles produce steeper foreshore slopes and cause plunging waves to break closer to the shore, as more wave energy is concentrated in a narrow zone the depth of disturbance is increased (Williams 1971). Whereas, on gentle sloping sand beaches the swash zone is separated from the breaker zone by a well developed surf zone. The disturbance on pebble beaches also varied according to the migration of pebble bed forms (Sherman 1991).

Further research highlighted that two peak values for the thickness of the moving sediment layer were identified. It would be expected that the greatest depth of disturbance would be associated with the break point, however there was also a second peak in the swash zone. Waves do not lose all their energy and form in one place, but continue to move up the foreshore as swash (Inman et al 1980 and Kraus 1985).

The review of the literature highlights that the depth of disturbance on beaches is attributed to the interaction between wave and beach sediment characteristics. In this research an experiment was undertaken to assess whether the distribution of sediment on a mixed beach influenced the thickness of the moving sediment layer.

7:12 TECHNIQUE FOR MONITORING BEACH DISTURBANCE

AIM 'TO INVESTIGATE THE DEPTH OF DISTURBANCE ON THE MIXED BEACH'

Objectives

1- To investigate the depth of disturbance on the mixed beach for the range of wave and tidal conditions.

2-To assess the variations in the depth of disturbance alongshore and cross shore.

The depth of disturbance of the beach face was monitored from the changes observed in vertical pebble cores. To record changes in the depth of disturbance of the beach face vertical pebble cores of a known length were inserted into the beach face. The vertical cores were made up of sphere shaped fluorescent pebbles of equal diameter, 1.5-2 cm. The pebbles were placed to a depth of 15 cm in the beach face. The pebbles making up the cores were numbered with respect to the beach face i.e. number ten was at the surface and number one was at the base of the core (figure 7:21). A plastic insertion sleeve ensured that the pebbles were positioned in the vertical core in the correct order. The cores were then packed with beach sediment to ensure the structure of the beach face was retained. The vertical pebble cores were positioned adjacent to the pebble tracer deployment points at the various longshore and cross shore sites to monitor the spatial variations in the disturbance of the beach face (figure 5:3). Marker stakes were located in the beach face adjacent to the pebble cores, but at sufficient distance to prevent scour. These marker stakes enabled the cores to be relocated after each tide. In addition, masking tape was put around the stakes at the level of the beach face to assess changes in the level of the beach face as a result of cross shore sediment transport that accompanies changes in the tide level (plate 7:1, 7:2).

RECORDING PROCEDURE FOR THE VERTICAL PEBBLE CORES

Careful excavation of the vertical pebble cores was required to ensure the remaining intact pebble core was not disturbed. As the initial length of the pebble core was known then the maximum depth of the disturbance could be calculated from the tracer number at the top of the intact core. In addition, the thickness and type of any fresh sediment deposited on top of the remaining core indicated whether there had been a net gain or loss in the thickness of the beach sediment layer in motion. The core results represented a time averaged maximum thickness of the transported layer once the beach face that had come to rest. The position of the displaced core pebbles indicated the direction of longshore transport. The pebble cores were then made up again with respect to the beach face on subsequent tides

Plate 7:1 Vertical Pebble Core.

Plate 7:2 Excavation of the vertical pebble cores.

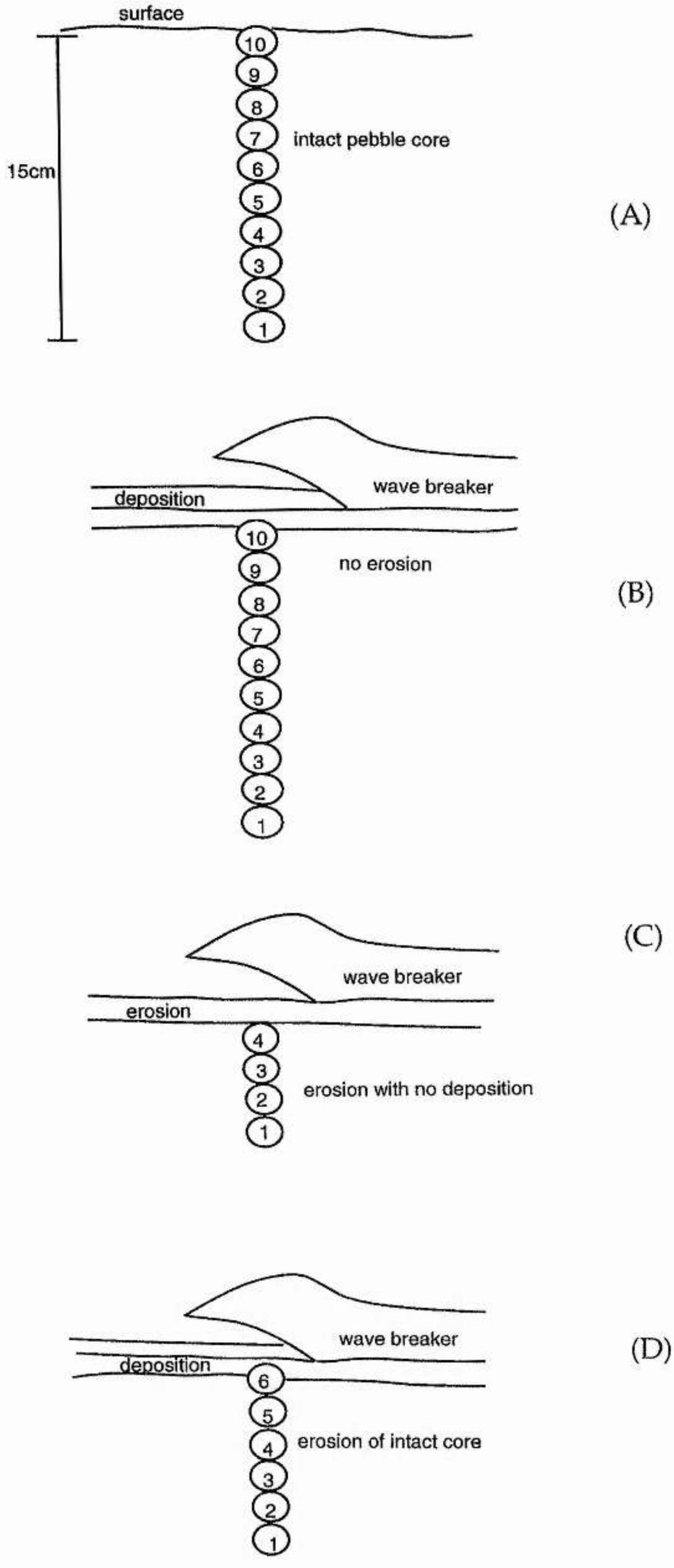


Fig 7:21 Vertical Pebble cores (a) intact core
(b) deposition with no erosion
(c) erosion with no deposition
(d) erosion and deposition

7:13 RESULTS DISTURBANCE OF THE MIXED BEACH

The root mean squared breaking wave height, the wind speed and the wave angle of approach were correlated with the disturbance of the beach face, to establish if these wave parameters influenced the thickness of the moving layer. The wave parameters were combined in the calculation of the longshore wave energy flux and correlated to the mean disturbance of the beach face. For simplicity, the changes in the vertical core results are described according to the low, moderate and high wave energy classification, outlined in section 6:1 Table 6: 2.

LOW WAVE ENERGY CONDITIONS

In low wave energy conditions, the wind speeds recorded were less than 10 miles per hour, and the breaking wave heights generated were no more than 0.3 metres. Consequently, the wave power exerted alongshore was less than 500 (N/m/s). The mean depth of disturbance recorded on the beach face was approximately 3 cm which represented a mobile layer of sediment undergoing longshore transport which was only one pebble diameter thick (figure 7:1). The wave sector from which the waves approached influenced the disturbance of the beach face (Table 7:1). The disturbance of the beach face was compared when waves approached from the south sector, the southeast sector and the southwest sector (figure 7:2). The disturbance of the beach face associated with waves that approached from the southeast sector was double the disturbance associated with waves from the south sector.

WAVE SECTOR	DISTURBANCE (CM)
south sector	1.5-2
southeast sector	3-4
southwest sector	2.5-3

Table 7:1 Mean disturbance in low wave energy conditions.

The changes in the vertical cores when subjected to low energy waves from the different sectors are illustrated in more detail (figures 7:4a-7:6a). The dominant waves from the southeast sector arrived at the shoreline with wave angles up to 20 degrees, consequently more wave energy was dissipated on the foreshore and the mean disturbance was 3-4 cm (figure 7:4a). The disturbance on the lower foreshore and in the swash zone exceeded the thickness of the sediment layer of fresh deposition. Waves with heights of 0.25-0.30 metres which approached the shoreline from the southwest sector also arrived at an oblique angle between 15-20 degrees, however the mean disturbance associated with these locally generated waves was only 2.5 cm (figure 7:6a).

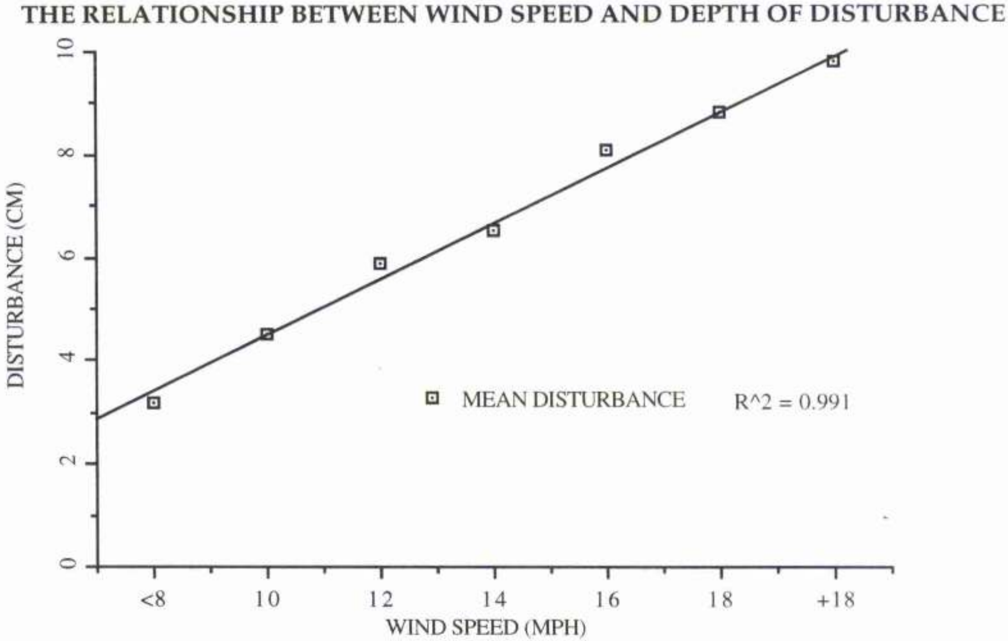


Fig 7:1 Disturbance according to wind speed.

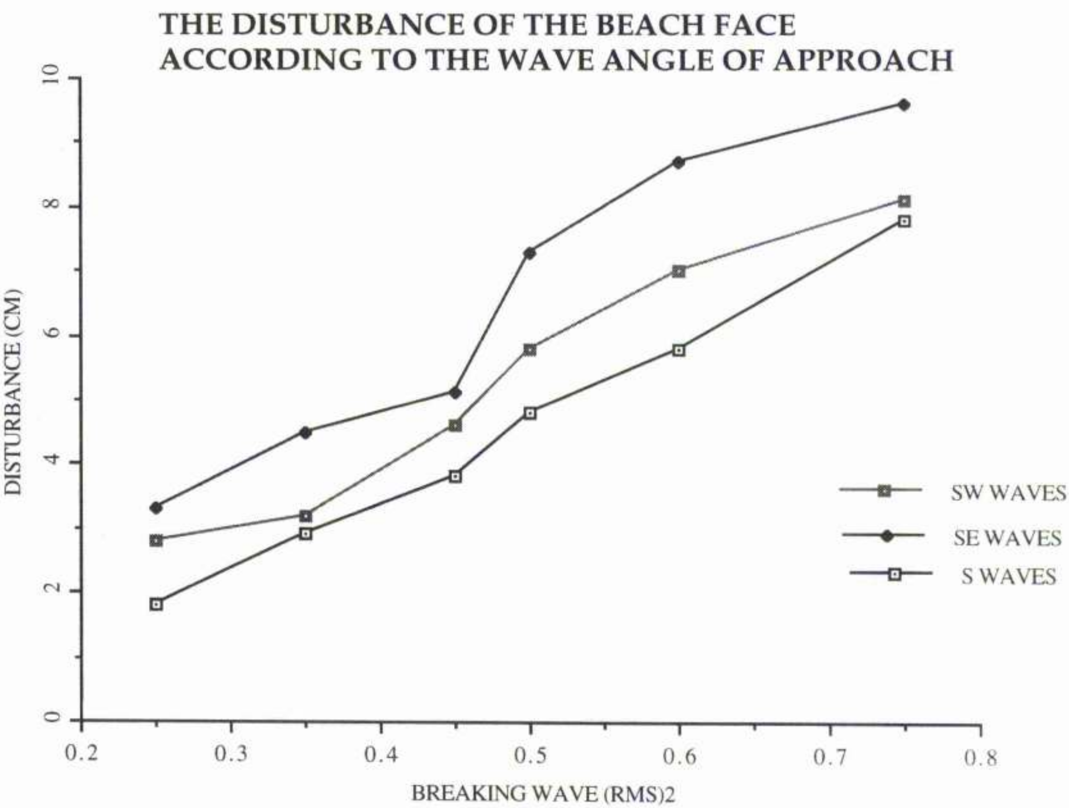


Fig 7:2 Disturbance according to the wave sector and wave height.

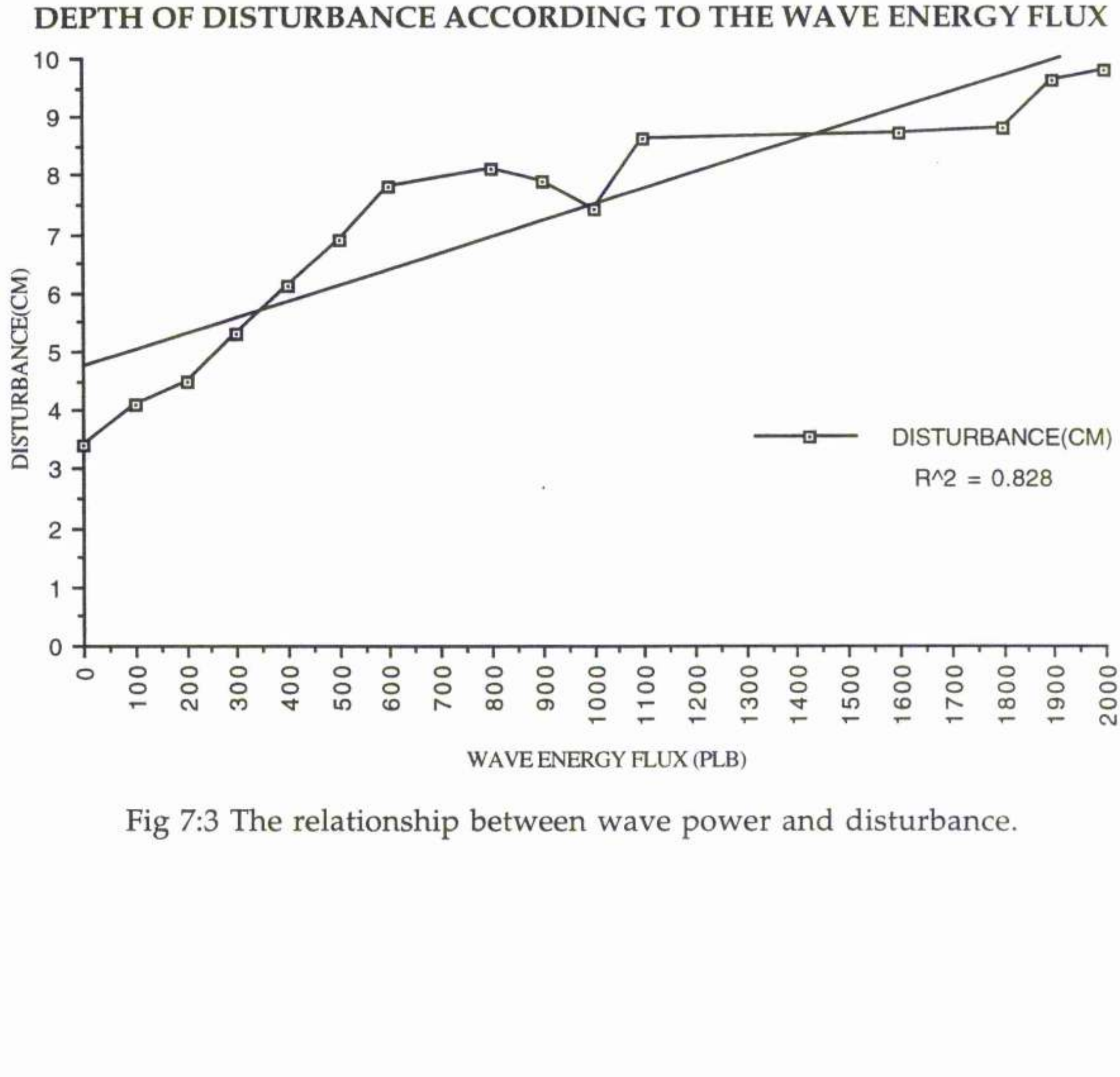


Fig 7:3 The relationship between wave power and disturbance.

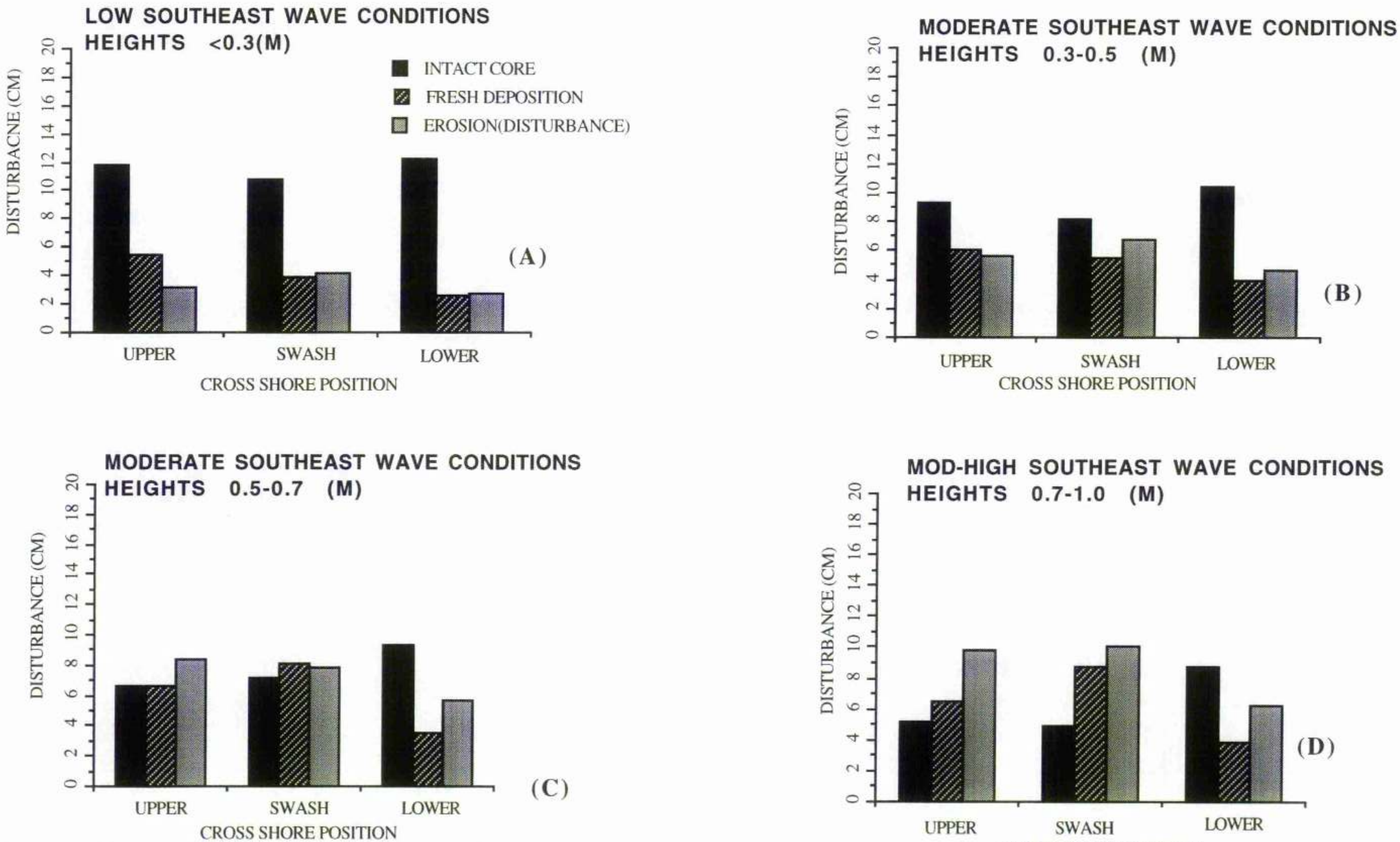


Fig 7:4 A-D Disturbance according to wave height southeast sector.

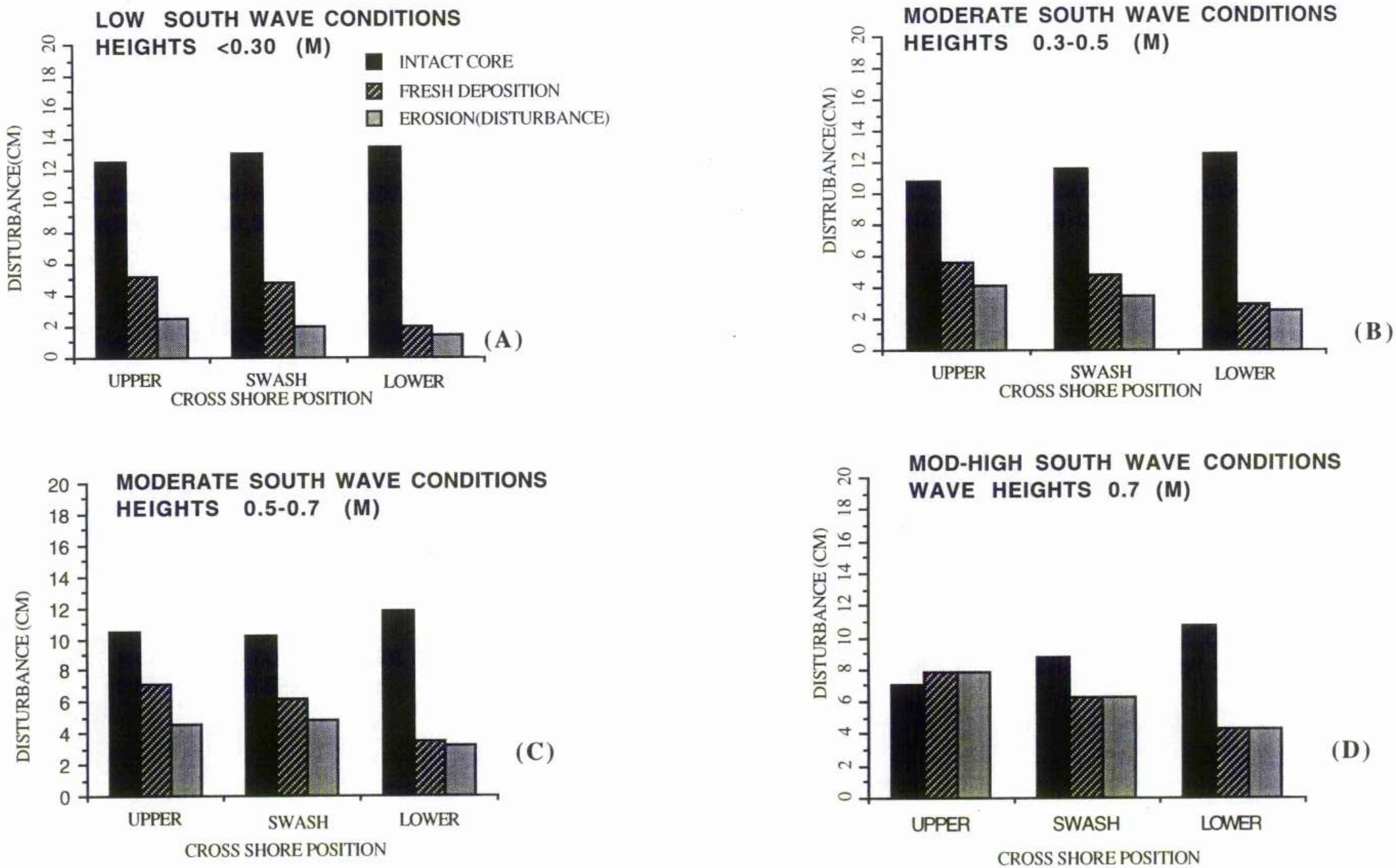


Fig 7:5 Disturbance according to wave height south sector

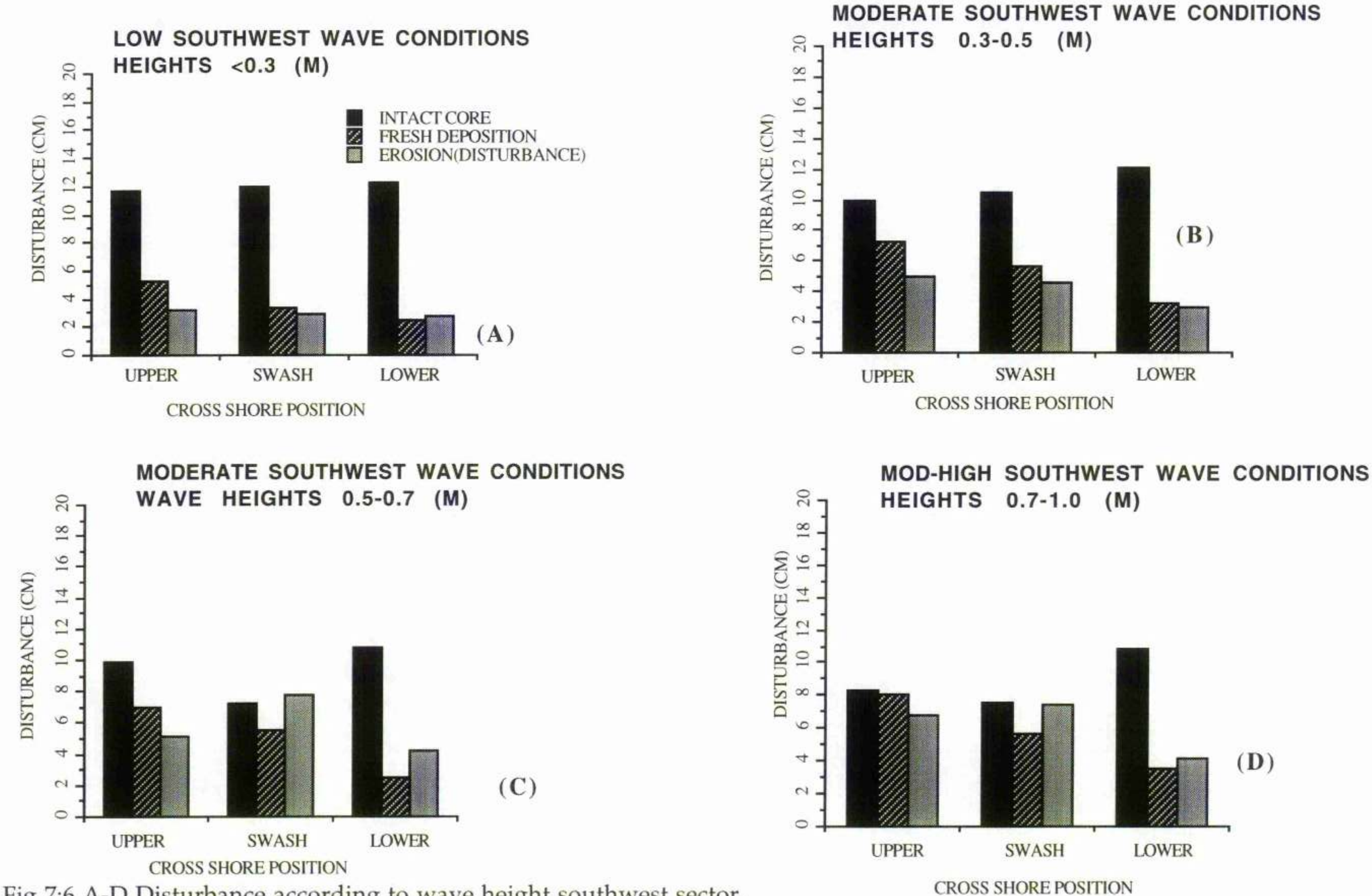


Fig 7:6 A-D Disturbance according to wave height southwest sector.

Waves from the south sector approached normal to the shore, consequently the wave power exerted alongshore was less significant. The mean thickness of sediment undergoing longshore transport was only 1.5-2 cm (figure 7:5a). When the waves approached from the south sector, the thickness of the sediment deposited in the layer above the remaining intact core exceeded the disturbance. The deposition varied in thickness from 2-6 cm and increased in the cross shore direction towards the upper foreshore. This supports the upshore transport of the tracer pebbles that was most significant for waves from the south sector which dispersed their energy upshore (section 6:14).

MODERATE WAVE ENERGY CONDITIONS

In moderate wave energy conditions, wind speeds varied from 10-14 mph and the breaking wave heights ranged from 0.30 to 0.70 metres. Consequently, the wave energy flux rose from 500 to 1000 (N/m/s) and the mean disturbance on the beach face increased from 4.5 cm to a maximum of 8 cm. The significance of the correlation between the disturbance and the increasing wave power is represented by the regression value of R^2 0.83 (figure 7:3). The disturbance of the beach face was attributed to an increase in shear stress exerted on the beach face as a result of plunging waves of greater height (figure 7:2). At wave heights of 0.60 metres the disturbance of the beach face was 3-4 cm greater than it had been in low wave energy conditions. The disturbance reflected a moving layer of sediment undergoing longshore transport that was a few pebble diameters thick.

WAVE SECTOR	MEAN DISTURBANCE (CM)
south sector	4.5
southeast sector	7.3
southwest sector	6.8

Table 7:2 Mean disturbance in moderate wave energy conditions.

In moderate wave energy conditions the changes recorded in the vertical pebble cores are illustrated in more detail in (figures 7:4-7:6 b/c). The disturbance of the beach face was most significant when waves approached from the southeast sector (Table 7:2). Southeast waves of 0.30-0.50 metres in height resulted in a mean disturbance of 4-6 cm (figure 7:4b).With an increase in the wave height to 0.50-0.70 metres the disturbance of the beach face increased to 6-8 cm and the disturbance of the beach face exceeded the fresh deposition (figure 7:4c). Whereas, the mean disturbance of the beach face associated with southwest waves was between 3 and 5 cm and 5 and 7 cm, for wave heights of 0.30-0.50 metres and 0.50-0.70 metres respectively (figure 7:6 b/c). Moderate waves that approached normal to the shore from the south sector had a maximum disturbance of 5 cm and the layer of fresh deposition exceeded the depth of disturbance (figures 7:5 b/c).

HIGH WAVE ENERGY CONDITIONS

In high wave energy conditions the mean wave heights recorded were 0.70 metres. In these conditions the mean disturbance of the beach face was up to 10 cm (figure 7:2). As the wind speeds increased a significant correlation was made with the disturbance of the beach face, which accounts for the regression value of R^2 0.99. At wind speeds of 16-18 mph the disturbance of the beach face was between 8 and 9 cm, which was three times the disturbance recorded at wind speeds below 10 mph (figure 7:1).

The wave energy flux calculated for the high wave energy conditions was between 1000 and 2500 (N/m/s). As the wave power rose the disturbance of the beach face did not increase as rapidly as it had done in moderate wave energy conditions, this is represented by the trend of the curve fit line (figure 7:3). When compared with (figure 7:2) it is clear that the dominant southeast waves resulted in approximately 2 cm more disturbance of the beach face than waves from the other sectors (Table 7:3). Furthermore, the depth of disturbance associated with waves from the southeast increased more steadily with an increase in the wave height than waves from the other sectors.

WAVE SECTOR	DISTURBANCE (CM)
south sector	4-5
southeast sector	7-10
southwest sector	5-8

Table 7:3 Mean disturbance in high wave energy conditions.

Figures 7:4-7:6d illustrate the changes in the vertical cores in high wave energy conditions. Waves from the southeast sector disturbed the mixed beach face up to a maximum depth of 10 cm. Furthermore, the southeast waves resulted in 2-3 cm more disturbance than fresh deposition, which was indicative of a net loss and erosion of the foreshore (figure 7:4d). Whereas, southwest waves had a maximum disturbance up to 8 cm and waves from the south sector had a maximum disturbance of 5 cm. Waves from the south sector resulted in a layer of deposition that was 2-3 cm thicker than the depth of disturbance (figure 7:5d).

Storm events doubled the thickness of the mobile layer recorded in moderate to high wave energy conditions. The most significant disturbance related to the development of storm cusps in which the disturbance reached 15-20 cm. The wave energy reflected from the cusps resulted in local longshore variations in the disturbance of the mixed beach foreshore.

7:14 CROSS SHORE VARIATIONS IN THE DEPTH OF DISTURBANCE

The vertical cores in (figures 7:4-7:6) permitted comparison of the disturbance and deposition at different cross shore positions; on the lower foreshore, the mid foreshore (or swash zone) and on the upper foreshore. It was assumed that the disturbance on the lower foreshore would be greater than elsewhere on the foreshore, as high shear stress was generated by the turbulence of the breaking waves. However, this was not the case, up to 2 cm more disturbance was recorded in the cores corresponding to the mid and upper foreshore which were positioned within the active swash zone.

Observations in the beach level at the marker stakes revealed that systematic changes in the disturbance of the vertical cores corresponded to cross shore sediment transport as the tide level varied between 5.8 metres at Spring tides and 4.1 metres at Neap tides (figures 7:7a/b). When the high tide level rose from 4.5 to 5.8 metres, the disturbance on the mixed beach foreshore was greatest within the active swash zone (figure 7:7a). When the high tide level was at 5.6 metres, the disturbance on the mixed beach became more significant on the upper foreshore. With a rising tide level the peak deposition was initially in the swash zone, then the deposition became more prominent on the upper foreshore. This change in the peak deposition was associated with the accretion of pebbles at the still stand of high water.

When the high tide level fell from 5.4 metres to 4.5 metres, the active wave front no longer reached the upper foreshore. At the Neap tide level when the high tide level only reached 4.1 metres, the disturbance was greatest at cores corresponding to the lower foreshore where the wave front was active for a longer period of time (figure 7:7b). As the tidal range decreased there was a reduction in wave energy associated with the decreasing water depth. With a fall in the tide level, the peak deposition corresponded to the position of the migrating swash berm (figure 6:11).

7:15 LONGSHORE VARIATIONS IN THE DEPTH OF DISTURBANCE

To assess the longshore variations in the disturbance of the beach face three transects were positioned alongshore, transect 1 was in the northeast and transect 3 was to the southwest (figure 5:3). The vertical pebble cores revealed that when the waves approached from the southeast sector the maximum disturbance was associated with transect one positioned in the northeast and the disturbance of the beach face declined towards the west (figure 7:8a). The variation in disturbance alongshore was attributed to the presence of the rock platform at low water in the northeast. The rock platform increased the wave height and generated turbulence,

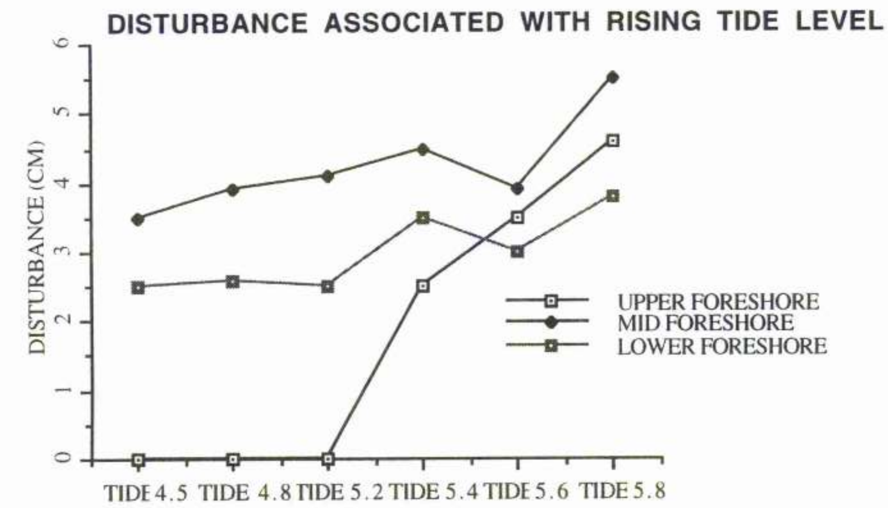


Fig 7:7(a) Disturbance associated with rising tide level.

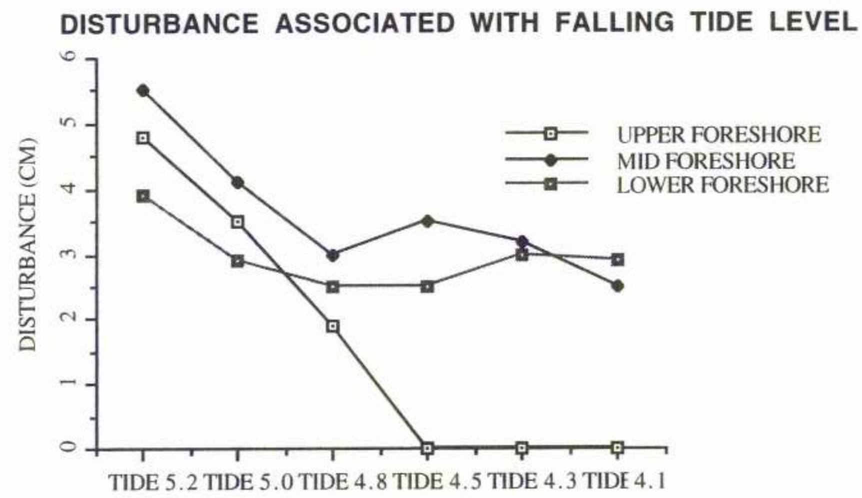
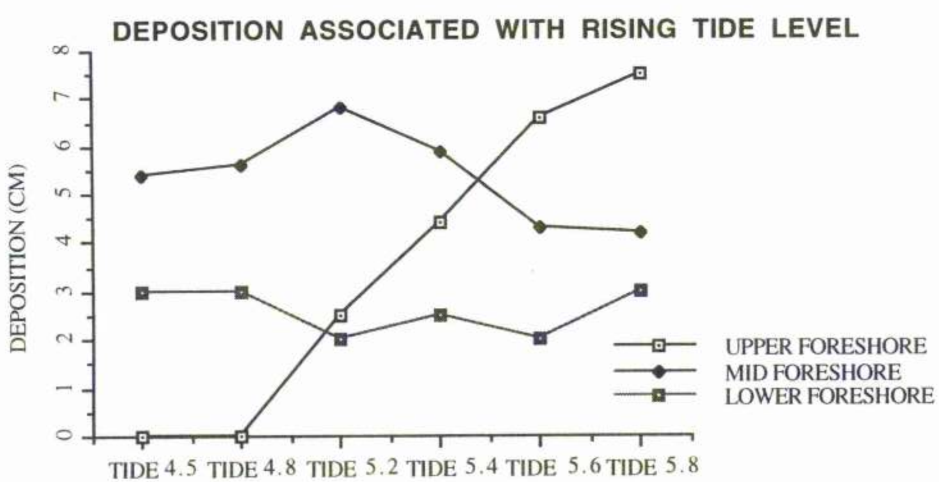
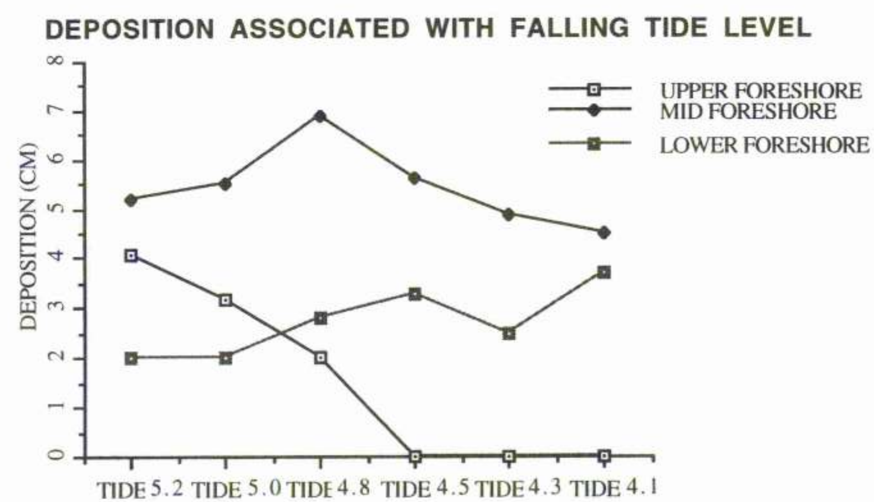


Fig 7:7(b) Disturbance associated with falling tide level.



Deposition associated with rising tide level.



Deposition associated with falling tide level.

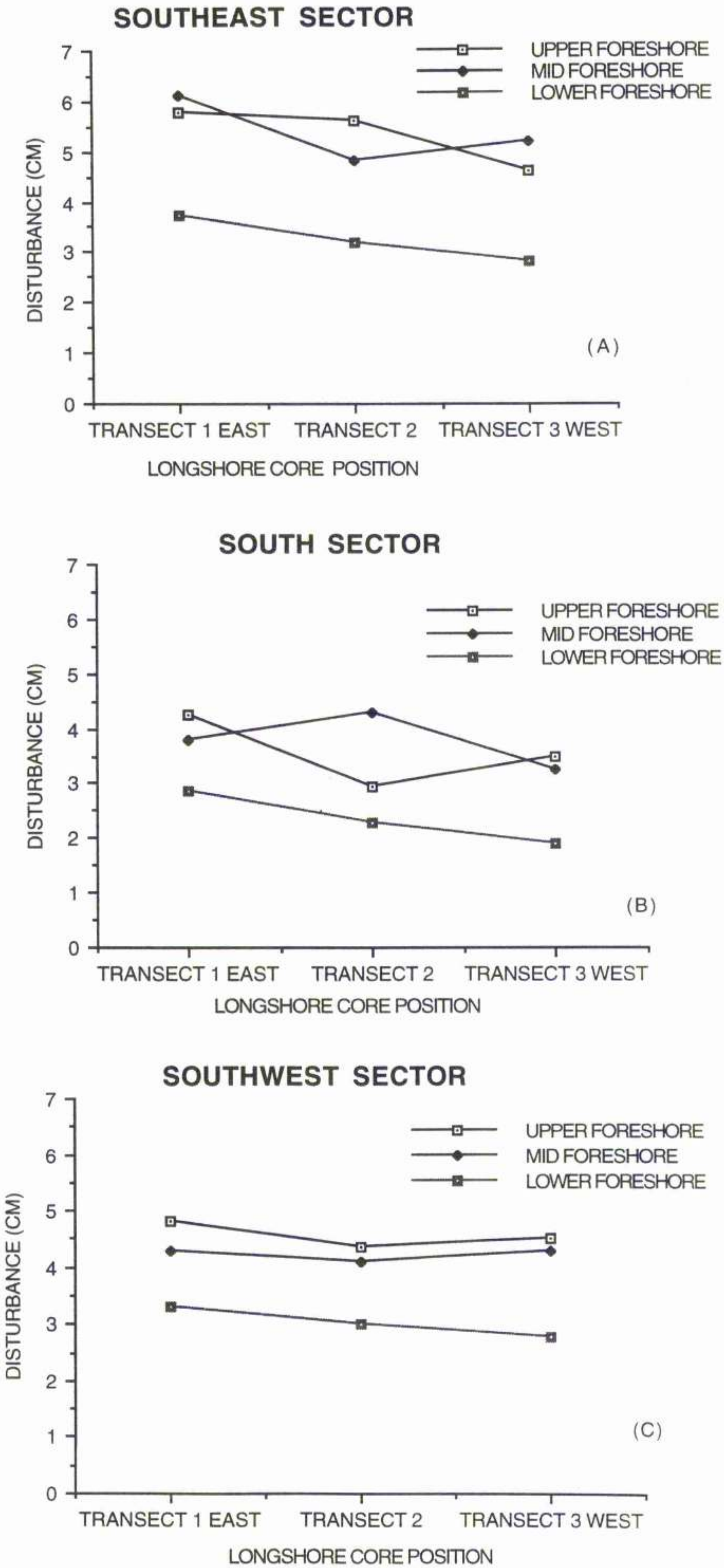


Fig 7:8 Longshore variations in disturbance.

that increased the shear stress responsible for the disturbance of the beach face. Furthermore, waves from the southeast sector underwent refraction and a higher proportion of wave power was dissipated on the foreshore in the northeast. When the waves approached from the south and southwest sectors the longshore variations in the disturbance of the beach face were less significant as the wave energy was directed normal to the shore.

DISCUSSION

The changes recorded in the vertical pebble cores highlight that the thickness of the layer of sediment undergoing longshore transport was far from uniform. The disturbance and deposition varied spatially alongshore, cross shore and over time. These variations in the disturbance of the beach face correlated to the prevailing wave and tidal conditions. A significant correlation was made between the disturbance of the beach face as the wave height and wind speeds increased. Furthermore, the wave angle of approach had a definite control on the disturbance of the beach face. The dominant southeast waves arrived at an oblique angle to the shoreline and transferred a greater thickness of sediment alongshore in the mobile layer. Whereas, waves from the south approached normal to the shoreline and caused an upshore movement of sediment. This investigation also highlighted the fact that the vertical beach face structure influenced the disturbance of the beach face and consequently the sediment transport. The importance of the vertical beach structure is examined in section 10:1.

8:1 AN INVESTIGATION OF THE RESPONSE OF PEBBLE SIZE IN WAVE ACTION

In Section 6:1 the transport of coarse pebbles of different composition was examined. However, the coarse tracer pebbles only modelled a small proportion of the size spectrum of pebbles on the mixed beach, therefore the predicted transport rates must be treated with caution (plate 8:2). A smaller experiment was undertaken to compare the transport of fine and coarse pebbles on the mixed beach.

METHODS

Pebbles with diameters of 2 cm were selected from the mixed beach for the fine tracer pebbles. The coarse tracer pebbles had a long axis length between 6 and 8 cm. The fine and coarse tracer pebbles were composed of coal, sandstone and ironstone, so that the interaction of pebble size and composition could be observed. All the pebbles were coated in fluorescent paint to aid recovery following release in the beach system. A four kilogram weight of fine pebbles and 200 coarse tracer pebbles were mixed with the surficial pebbles on the beach at the deployment site that was positioned between the low and high water mark.

Simultaneous deployment of the fine and coarse pebbles took place in low wave energy conditions, then another deployment of tracers was made when moderate to high wave energy conditions prevailed (plate 8:1). Both deployments were made when the tide level was rising towards Spring tides and the wave conditions were monitored throughout the time the tracers were subjected to wave action. After each tide, visual tracer searches were undertaken at low water. The dispersion of the fine tracer pebbles were marked on a reference grid of the foreshore and the longshore and cross shore co-ordinates for the coarse tracer pebbles were recorded according to the procedure outlined in section 5:1.

The recovery rates for the fine tracer pebbles were approximately 50-60% of the injected total following one tide, thereafter the recovery of the fine tracer pebbles declined to 20% during the five day period of the tracer search. The mean longshore transport rates of the fine and coarse tracer pebbles were calculated for each tide and correlated to the wave height and the wave energy flux, to establish if the transport behaviour of the pebbles of the two size classes were influenced by the wave energy.

Plate 8:1 Fine tracer pebble deployment.

Plate 8:2 Pebble size variations on the mixed beach.

8:12 THE RESPONSE OF FINE AND COARSE PEBBLES IN WAVE ACTION

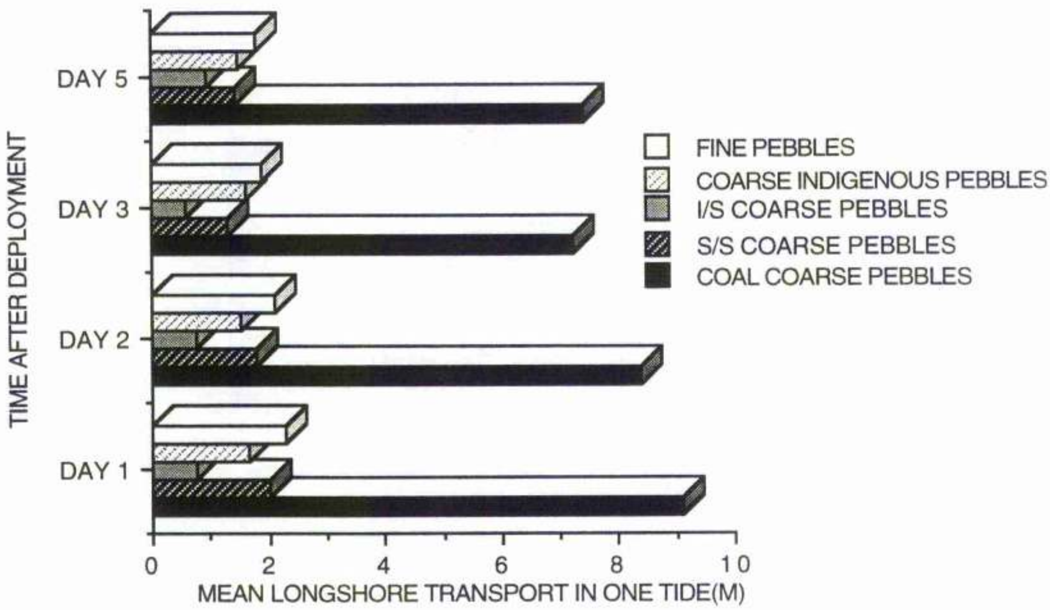
LOW WAVE ENERGY CONDITIONS

In low wave energy conditions, the fine tracer pebbles were entrained in preference to the coarse tracer pebbles, with the exception of the coarse coal tracer pebbles that were readily transported along the shore due to their unusual physical properties (figures 8:1). The transport behaviour of the coarse coal pebbles were outlined in more detail in (section 6:12). Up to wave heights of 0.40 metres, the fine tracer pebbles were transported more readily along the shore than the coarse indigenous sandstone and ironstone tracer pebbles (figure 8:4). The mean longshore transport of the fine tracer pebbles for one tide was approximately 2.3 metres. Whereas, the mean longshore transport for the coarse sandstone and ironstone indigenous pebbles was only 1.5 metres.

For the five day period in which low energy waves from the southeast sector prevailed, the mean longshore transport rates of the fine and coarse tracer pebbles were compared (figure 8:1). The initial transport of the fine tracer pebbles was significantly greater than the coarse sandstone and ironstone indigenous pebbles. However, five days after deployment the mean displacement of the fine tracer in one tide had decreased from 2.3 to 1.5 metres, despite the fact there had been no significant change in the wave parameters. Consequently, by day five of the survey the fine tracer pebbles were transported at nearly the same rate as the coarse sandstone tracer pebbles. Low energy waves from the southwest sector resulted in similar transport behaviour, with the fine tracer pebbles moving more readily than the coarse sandstone and ironstone tracer pebbles. However, the longshore transport rates associated with these waves were not as significant.

The final position of the fine tracer pebble centroid was up to 3 metres further along the shore, than the coarse sandstone tracer pebble centroid from the same deployment site. When compared to the coarse ironstone pebbles, the fine tracer pebble centroid was displaced 7 metres further along the shore (figure 8:5). In sharp contrast, the final position of the coarse coal pebble centroid was approximately 50 metres further along the shore than the fine tracer pebble centroid.

SOUTHEAST SECTOR
TRANSPORT OF FINE AND COARSE PEBBLES IN LOW WAVE ENERGY



SOUTHWEST SECTOR
TRANSPORT OF FINE AND COARSE PEBBLES IN LOW WAVE ENERGY

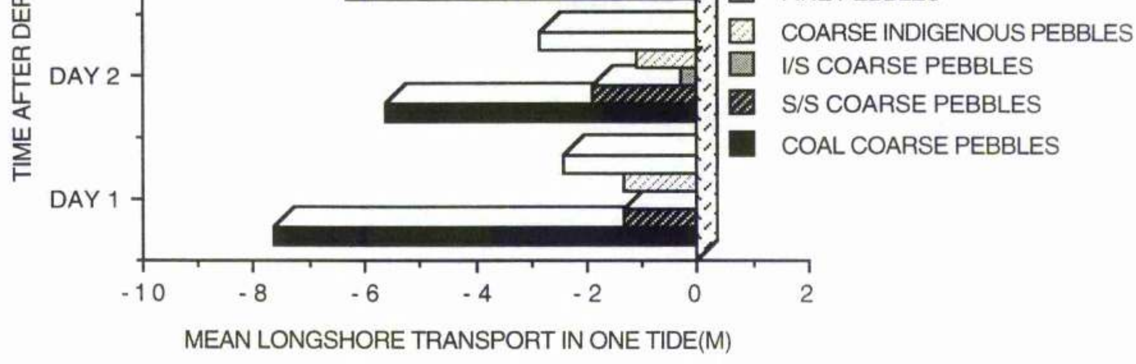


Fig 8:1 Transport of fine and coarse pebbles in low wave energy conditions.

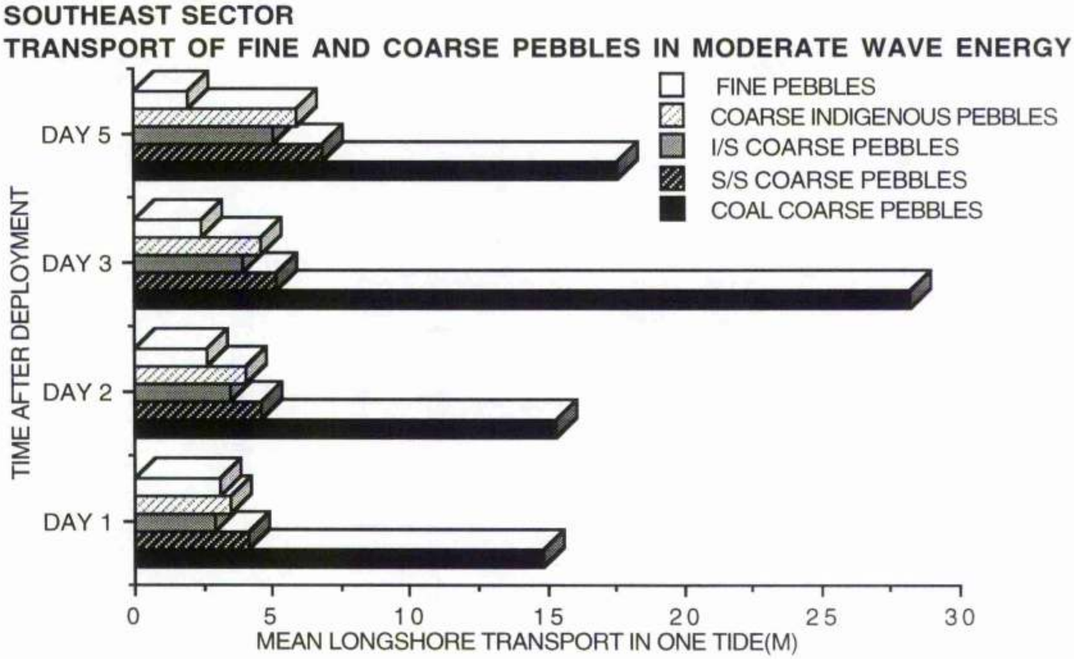
MODERATE TO HIGH WAVE ENERGY CONDITIONS

In moderate wave energy conditions, when the wave energy flux was 450 (N/m/s) and the wave height was 0.40 metres, the mean longshore transport rates of the coarse indigenous ironstone and sandstone pebbles and the fine pebbles were similar. The mean longshore transport rate for the fine and coarse pebbles was approximately 2.5 metres in one tide (figure 8:3/8:4). With an increase in the wave energy flux and at wave heights between 0.60 and 0.70 metres, the coarse indigenous ironstone and sandstone tracer pebbles were transported up to 2-3 metres further in one tide than the fine tracer pebbles. Furthermore, as the wave height increased the transport rate for the coarse tracer pebbles rose steadily whereas, the speed of transport of the fine tracer pebbles did not increase at a significant rate (figure 8:4).

During the period of moderate to high wave energy conditions, the mean tracer transport along the shore was calculated for each tide (figure 8:2). Following deployment, the initial rate of transport for the fine tracer pebbles was similar to the coarse tracer pebbles. The mean longshore transport in one tide for the fine tracer pebbles was between 2 and 3 metres. In subsequent tides, the longshore transport in one tide for the fine tracer pebbles decreased, whereas the mean longshore transport rate for the coarse indigenous sandstone and ironstone pebbles rose from 3 to 6 metres in one tide.

Five days after deployment, the coarse tracer pebble centroids were positioned significantly further along the shore than the fine tracer pebble centroid (figure 8:5). The coarse sandstone centroid was 43 metres from the initial deployment site, whereas the fine pebble centroid was displaced 24 metres along the shore from the same deployment site. Even the coarse ironstone tracer pebble centroid was up to 10 metres further along the shore than the fine tracer pebble centroid, despite the fact the pebbles had been subjected to the same wave conditions.

The coarse and fine coal tracer pebbles responded differently in wave action in comparison to all the other tracer pebbles. The coarse coal tracer pebble centroid was at least 100 metres further along the shore than the centroid positions of the other tracers.



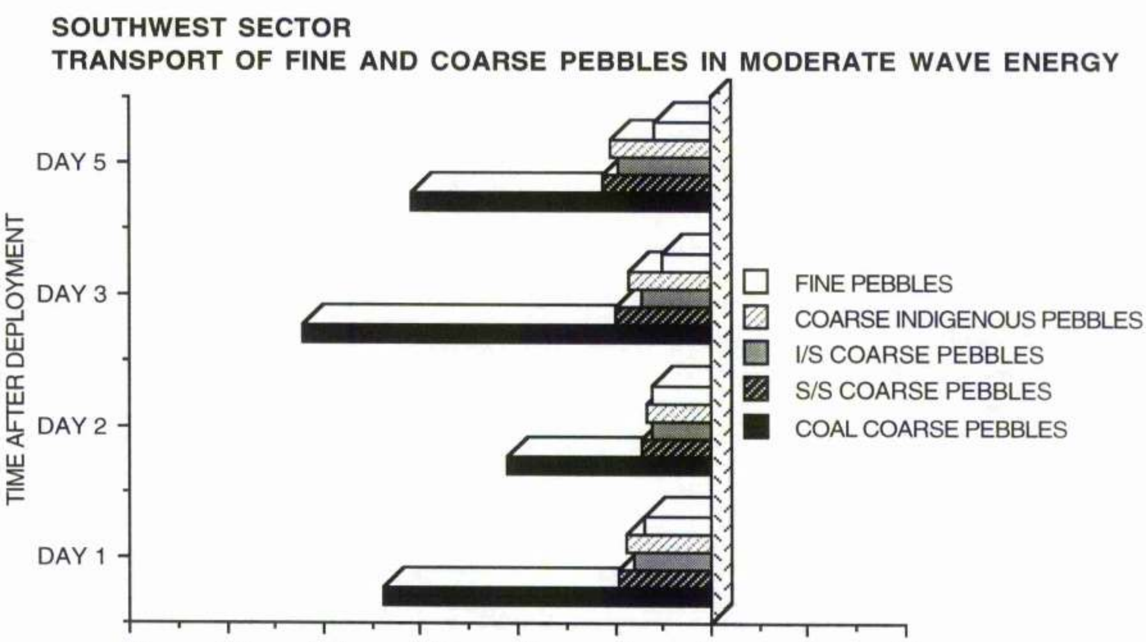


Fig 8:2 Transport of fine and coarse pebbles in moderate wave energy.

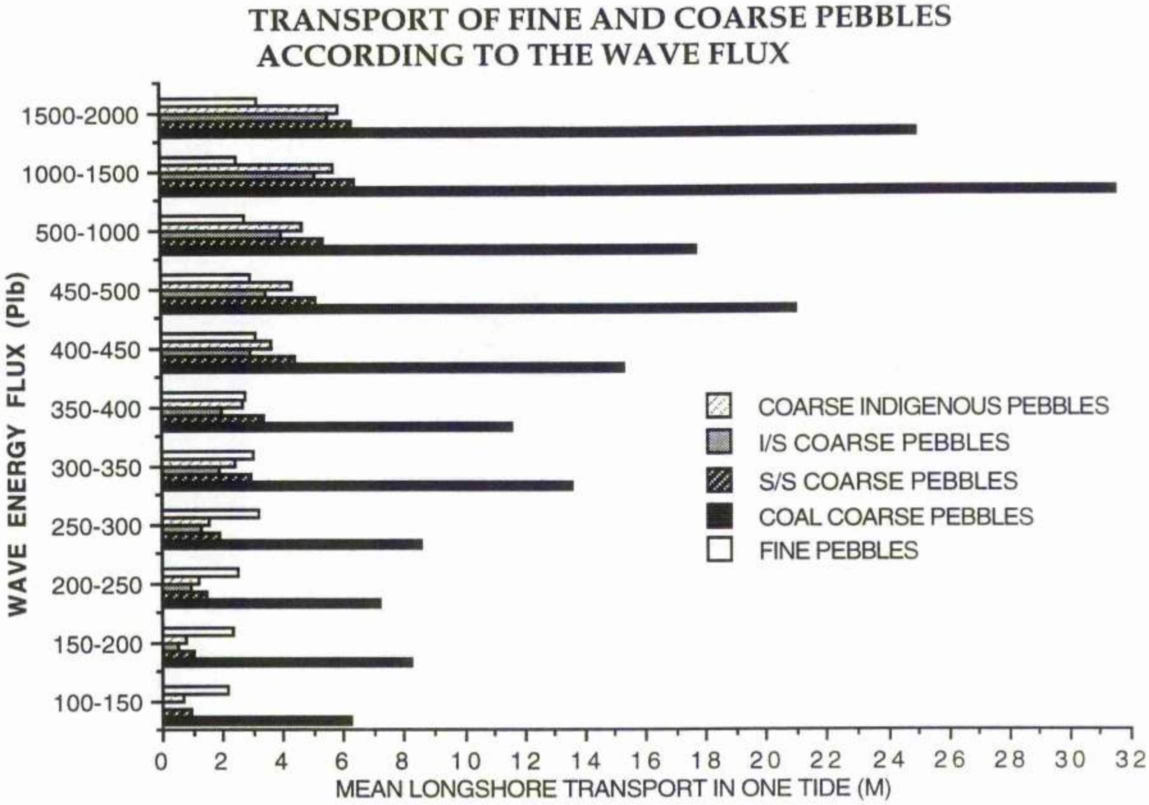


Fig 8:3 Transport of fine and coarse pebbles according to the wave energy flux.

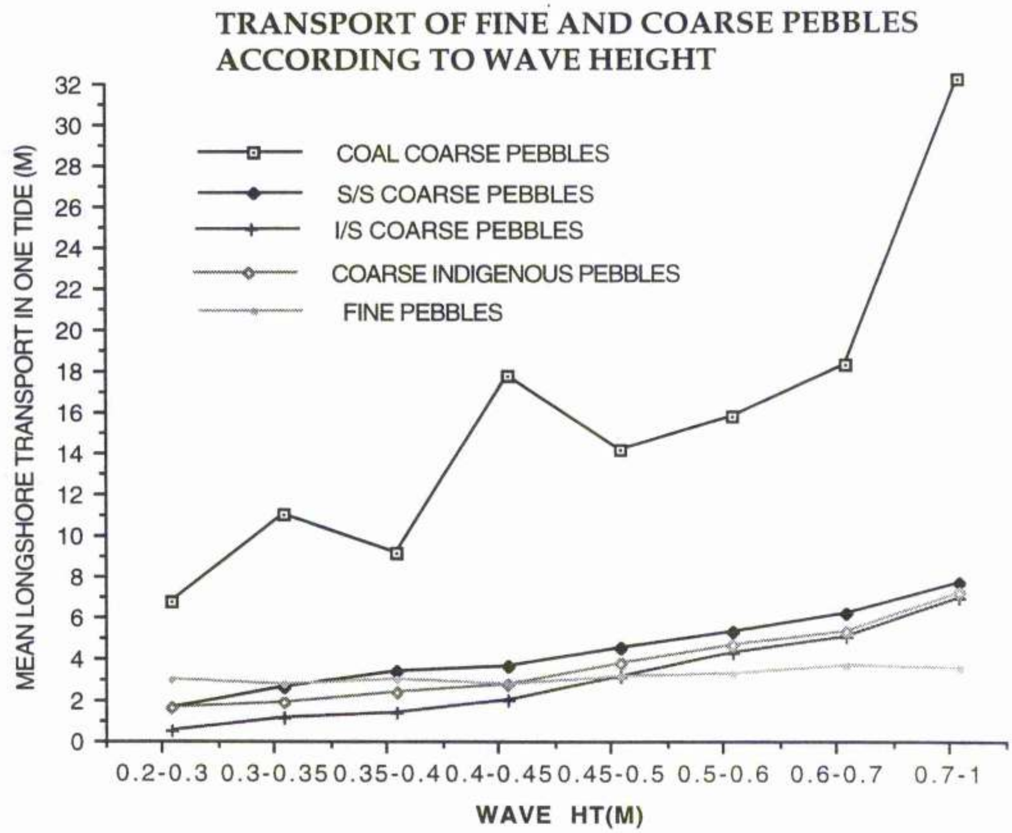


Fig 8:4 Transport of fine and coarse pebbles according to the wave height.

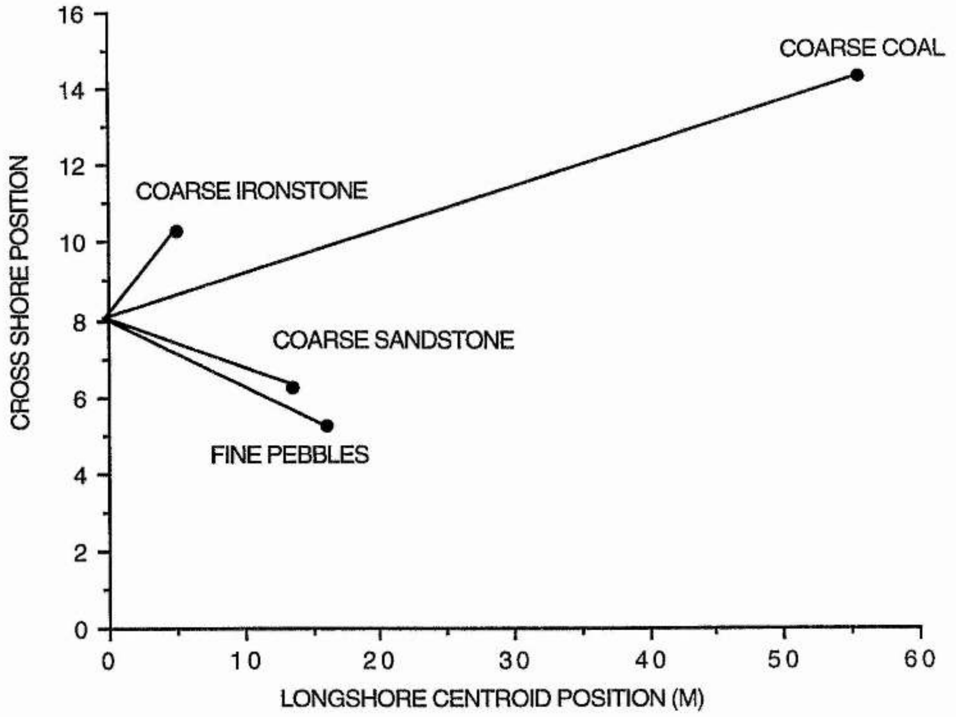
8:13 DISCUSSION THE RESPONSE OF FINE AND COARSE PEBBLES IN WAVE ACTION

The transport behaviour of the fine and coarse tracer pebbles was dependent on several interrelated factors. The duration of time following tracer deployment, the wave power and the pebble composition.

Observations revealed that in low wave energy conditions the fine tracer pebbles were entrained from the immobile framework of coarse ironstone pebbles, with the exception of the coarse coal pebbles that were entrained even more readily than the fine tracer pebbles. With an increase in the wave energy, the coarse tracer pebbles were entrained in preference to the fine tracer pebbles from the mixed bed. This was attributed to the packing and sorting characteristics of the mixed beach face (plate 8:2). Coarse tracer pebbles protruded from the mixed bed and increased the roughness of the boundary layer. In consequence, local turbulence was generated that enhanced the lift and drag forces for the entrainment of the coarse pebbles. Whereas, the close packing, the limited protrusion and the similarity in size of the fine pebbles, reduced the ease at which the fine tracer pebbles were entrained. The responses of fine and coarse pebbles were clearly dependent on wave energy (figure 8:6). The findings support the work of Jolliffe (1964) who correlated the transport of different sizes of pebble to particular wave heights. Small waves moved fine pebbles, however as wave energy increased the coarse pebbles moved further than the fine pebbles.

Following an initial rapid transport, the fine tracer pebbles became rebedded into the beach due to drag from the downward percolation of the swash. Observations revealed that the fine tracer pebbles became trapped in the voids between the adjacent coarse pebbles and were less readily transported in subsequent swash action (figure 8:6). In contrast, once in motion the larger pebbles had high inertia that aided transport. As the coarse pebbles were deposited after the fine pebbles had created the beach framework, the coarser pebbles were more exposed to the next oncoming swash. Observations revealed that the pebbles of the different sizes interacted in transport. As the coarse pebbles were larger than the surrounding pebbles, it was speculated that the coarse pebbles were able to roll or slide over a bed of finer pebbles. The larger pebbles moving in saltation leapt onto a bed of crowded finer pebbles which were rolling, but because of the packing of the finer pebbles, the larger pebbles were not incorporated into the beach face (Isla 1993). Consequently, the larger pebbles were relifted and remained in motion as part of the mobile layer, overpassing the fine tracer pebbles.

TRACER CENTROID POSITIONS LOW WAVE ENERGY



TRACER CENTROID POSITIONS MODERATE WAVE ENERGY

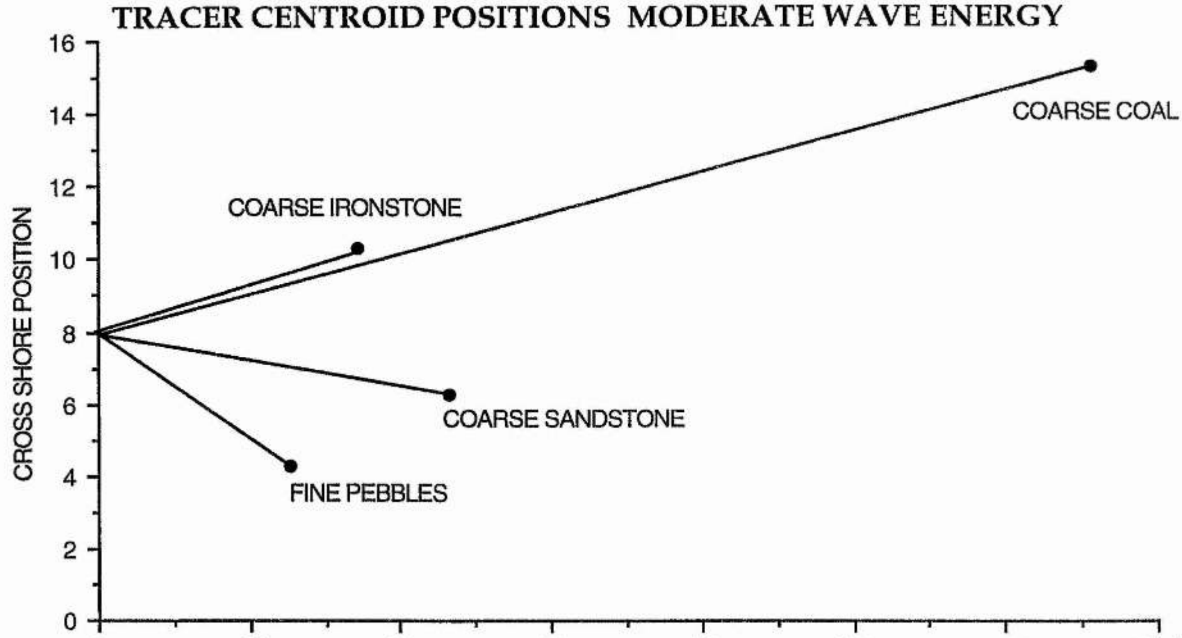


Fig 8:5 Coarse and fine pebble tracer centroids.

Plate 8:3 Coal bands 'hydraulic sorting'.

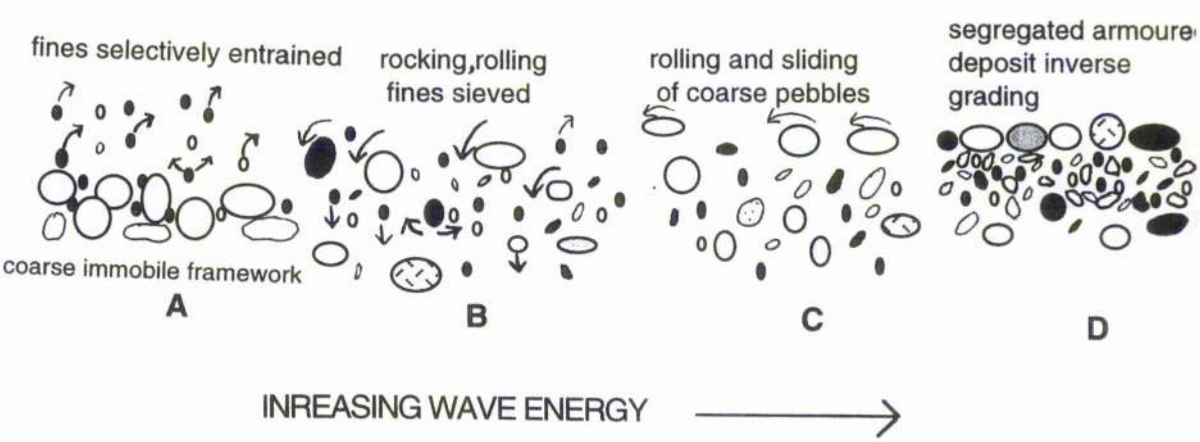


Fig 8:6 The response of coarse and fine pebbles in wave action.

A similar phenomenon of selective transport in wave action according to pebble size was described by Carr (1979), Moss (1963). Although it is not illustrated in the results, the fine pebbles were composed of ironstone, sandstone and coal, so that the interaction of size and composition could be observed. The fine coal pebbles behaved similarly to the coarse coal pebbles and were readily entrained within one swash flow and clustered at the watermark to form diagnostic coal bands (plate 8:3), or the fine coal pebbles were carried in suspension offshore, a few were recovered at extreme distances up to 300 metres alongshore. The fine ironstone and sandstone tracer pebbles displayed similar transport behaviour, therefore it is assumed that with a decrease in size the differential transport of the ironstone and sandstone pebbles is reduced.

In conclusion, the tracer results highlight that in addition to the variation in pebble composition, the distribution of pebbles of different size influenced the initiation and subsequent transport of pebbles on the mixed beach.

9:1 TRACER SAND EXPERIMENT

On the mixed beach in addition to the spectrum of pebble sizes, sand formed a significant proportion of the beach sediments, varying from less than 10% to 70%. The increase in the proportion of sand on the foreshore was attributed to a combination of wave and tidal effects. At Spring tides when the water level was high, sand was transported onshore from offshore sinks. Long period swell waves also put sand into suspension from offshore sinks. The distribution of sand was mainly restricted to the mid and upper foreshore, where it formed a surface cover that varied in thickness from 1 cm to a maximum of 10 cm (plates 9:1). With a change in the water level, wave height or wave angle of approach the sand was transported rapidly offshore, uncovering the pebbles below. To gain insight into the transport dynamics of pebbles in the presence of sand on the mixed beach, tracer sand was deployed simultaneously with coarse tracer pebbles.

Objectives;

1-To investigate the rate and direction of sand transport on a mixed beach.

2-To examine the disturbance of the mixed beach with a high proportion of sand.

3-To investigate how the presence of sand on the mixed foreshore influenced the rate and direction of pebble transport.

METHODS

The sand on the mixed beach varied in composition from a dark coarse sand with a high proportion of shale, sandstone and coal waste detritus fragments, to a lighter coloured sand composed of reworked quartz and feldspar. To examine the transport of the sand a tracer experiment was undertaken. The use of an artificial sand would not model the hydrodynamic characteristics of this particular beach sand, therefore sand was collected from the beach and stained. Various techniques have been used to stain sand (Crickmore 1976 and Yasso 1965). The successful method selected involved staining the sand using anthracene with chloroform, which caused the tracer sand to fluoresce purple when excited under ultra violet light.

To stain two kilograms of sand 10 g of anthracene was required. The anthracene was pulverised in a mortar, then taken into solution in 300ml of warmed chloroform. This mixture was then gently heated and stirred on a hot plate, ensuring that the mixture did not rise above 50°C. It was essential that the heating and mixing was carried out in a well ventilated fume cupboard. The solution was then added to the sand and thoroughly mixed. The sand was then left to dry at 20°C, to ensure the staining on the sand was uniform.

Plate 9:1 The distribution of sand on the mixed beach.

Plate 9:2 Tracer sand deployment trench.

DEPLOYMENT OF SAND AND PEBBLES ON THE MIXED BEACH

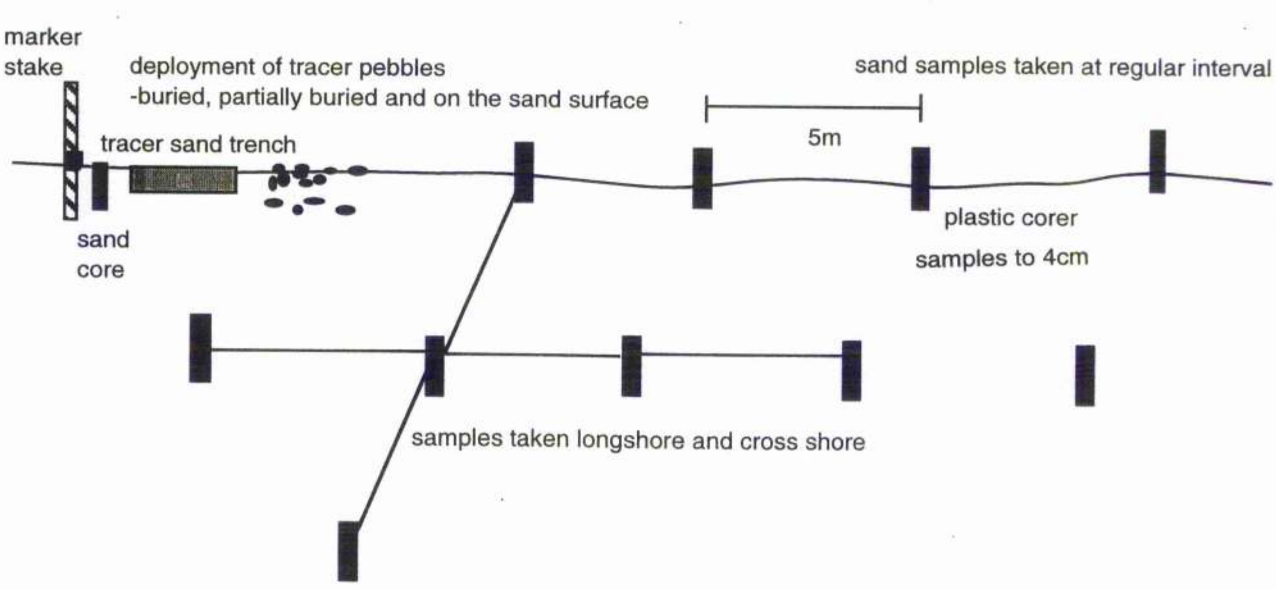


Fig 9:1 The deployment of tracer sand and pebbles.

DEPLOYMENT PROCEDURE FOR THE TRACER SAND

Deployment of the tracer sand into the beach face was undertaken when a significant proportion of sand composed the mixed beach foreshore. The deployment sites corresponded to positions along transects perpendicular to the shore between low and high water mark. At each site 18 kg of the fluorescent tracer sand was injected in a trench which was 4 cm deep, 50 cm wide and 100 cm in length (plate 9:2). The tracer sand was packed and saturated to model the textural characteristics of the beach face.

Alongside the trenches of fluorescent tracer sand, vertical cores of coloured sand were positioned to depths of 10 cm into the beach face. The procedure was similar to the vertical pebble cores described in (section 7:12). The sand cores were used to determine the disturbance on the mixed beach when sand covered the pebbles. The fluorescent tracer sand was not used in the vertical sand cores, as it was only visible in strong sunlight. A coloured sand with the same textural characteristics as the indigenous beach sand enabled the sand cores to be detected once positioned in the beach face. The sand core was inserted into the beach with the use of a plastic tube. Marker stakes were placed into the beach face, just beyond the position of the core to prevent scour. Masking tape was wrapped around the stake to mark the level of the beach face (plate 9:3) (figure 9:1).

Two hundred coarse pebble tracers were simultaneously deployed with the tracer sand. The aim of the pebble deployment was to investigate if the presence of sand on the foreshore of the mixed beach altered the response of pebbles in wave action. The tracer pebbles were divided into three groups, one group of pebbles were placed on the sand surface, another group were partially buried in the sand and the final group of tracer pebbles were buried to depths of 4-5 cm in the sand.

SAMPLING TECHNIQUES FOR THE TRACER SAND

Following the release of a known quantity of tracer sand into the beach face the wave parameters were monitored. After one tide sand samples were collected at regular longshore distances from the deployment site over a predetermined sampling grid on the beach foreshore that was 200x25 metres. The spacing of the sampling points is illustrated in (figure 9.3/4).

In the trial experiment the collection of sand samples involved the use of adhesive fablon sheets with an area 15x15 cm. The sheets were attached to a base block on a pole and a surface sample was collected by sticking the sand to the sheet. This method was unsuccessful as pebbles on the sand surface prevented an even sample of sand from being collected. Instead, a 0.5 kg volume sample was collected at each sample site by inserting a plastic coring tube to a depth of 5 cm (figure 9:1). The sand samples were placed into bags and labelled according to the X (cross shore) and Y (longshore) co-ordinates of the sampling grid with respect to the

Plate 9:3 Beach marker level and sand cores.

Plate 9:4 Tracer Pebbles buried in sand.

initial deployment site. The positions of the recovered coarse tracer pebbles were also recorded on the grid. Then the vertical sand cores were carefully excavated and the remaining intact coloured sand in the core was measured. In addition, the thickness of any fresh sand deposited on top of the core was recorded.

LAB ANALYSIS OF THE FLUORESCENT TRACER SAND

The sand samples were sieved when there was a high proportion of fine pebbles amongst the sand. This was typical of sand samples taken lower on the foreshore, as the sand was found as an interstitial component between the pebbles. After drying, the 0.5 kg sand samples were spread over a black wooden board. The tracer sand grains were then counted in each sample under an ultra violet light in a dark room (Komar 1969 and Sarrikostis 1986). It is essential that certain precautions were taken when using a ultra violet light. A protective face visor must be worn and all exposed skin must be covered. The tracer sand produced light emissions to short wave ultra violet light, with excitation the tracer sand fluoresced a purple colour. Purple emissions were also given off from shell fragments. Fortunately, the beach sand does not contain a high proportion of shell fragments and the shape of the shell fragments were distinguished from the tracer sand grains. The tracer counts were represented for a kilogram weight of sand.

9:12 RESULTS THE RESPONSE OF SAND ON THE MIXED BEACH

For each tide the dispersion of the tracer sand was illustrated on a grid of the foreshore. Contour lines were plotted joining positions of equal tracer sand concentration with distance from the deployment site. The tracer sand distribution was then used to determine the mean and maximum longshore distance and direction of sand transport. The sand results were then compared to the mean longshore transport of the coal, sandstone and ironstone tracer pebbles that had been subjected to the same wave conditions. From the changes recorded in the vertical sand cores the thickness of the mobile layer of sediment undergoing longshore transport was established. Furthermore, important observations were made as to the interaction of sand and pebbles in wave action on the mixed beach.

TRIAL DEPLOYMENT OF THE TRACER SAND

Following the deployment of the tracer sand in the trial experiment, high wave energy conditions prevailed, in conjunction with high tides. The root mean squared wave heights recorded were 0.72 metres and the wind speeds reached 18 mph from an east-southeast direction. The wave angle of approach was therefore oblique to the shore at an angle of 35 degrees. On one tide the sand on the foreshore was almost completely removed and pebbles dominated the foreshore of the mixed

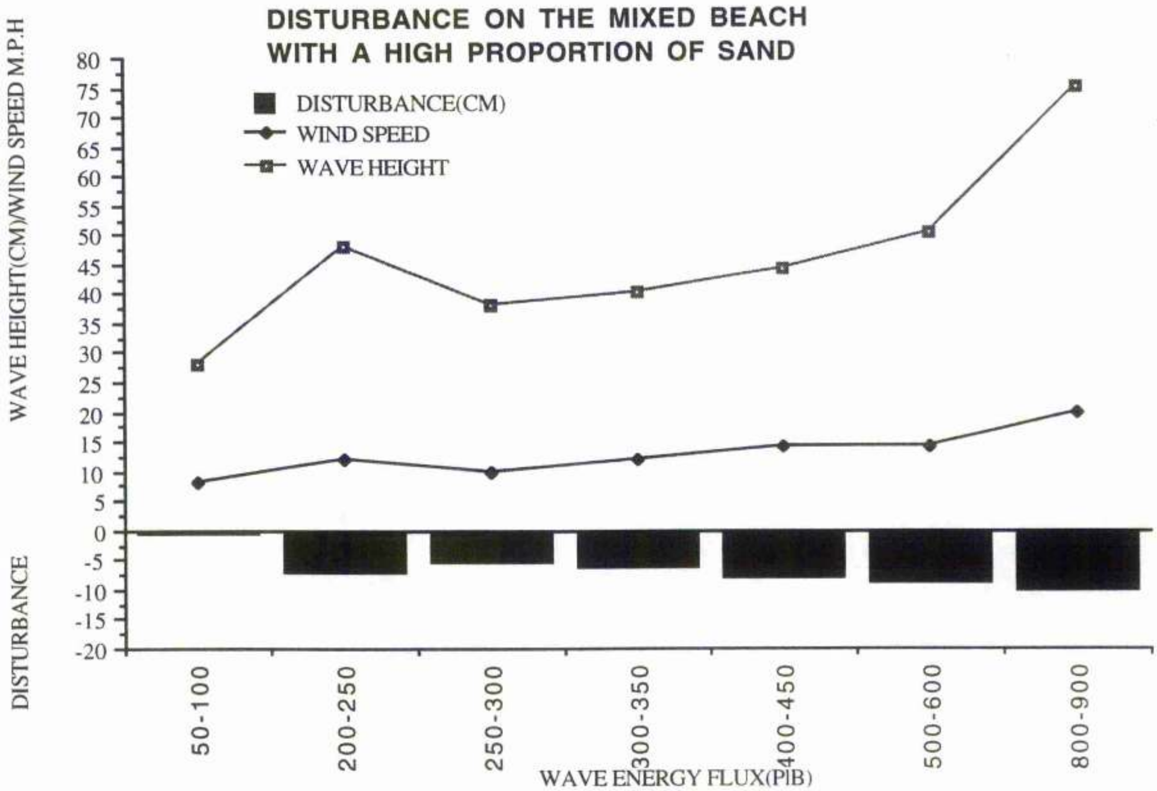


Fig 9:2 Disturbance of the mixed beach
when sand overlies the pebbles.

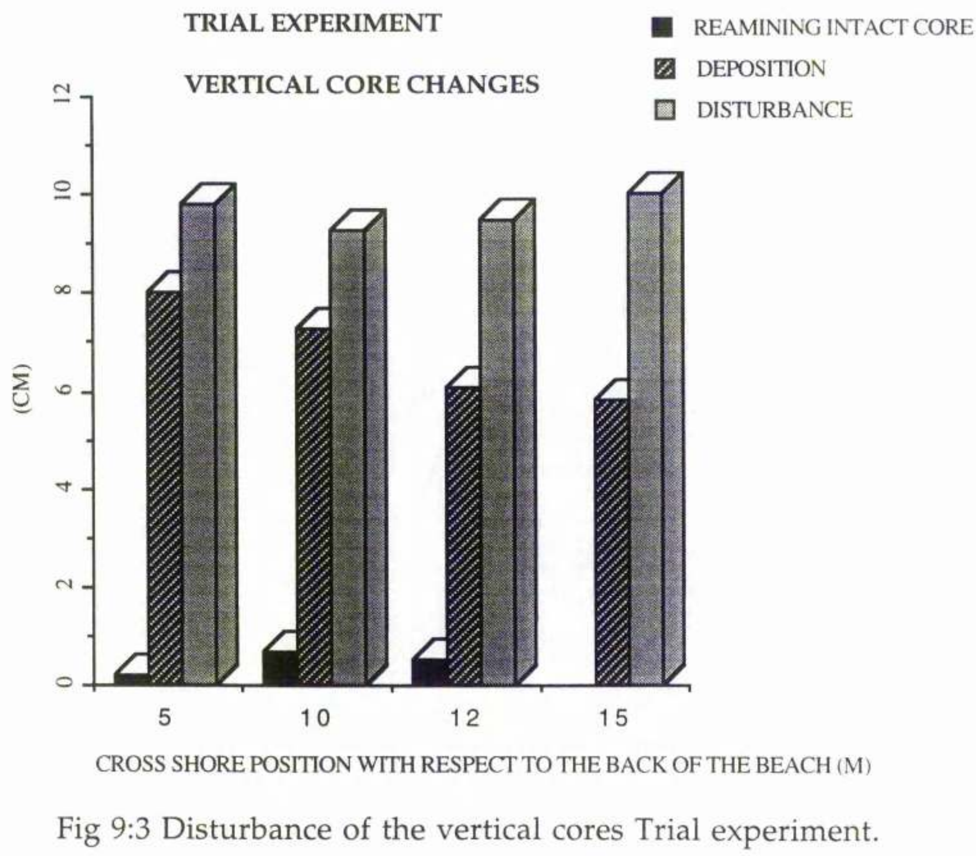


Fig 9:3 Disturbance of the vertical cores Trial experiment.

beach. The only tracer sand that was recovered was an interstitial component intermixed with the fine and coarse pebbles. The amount of tracer sand recovered was insignificant to determine any longshore patterns of movement, therefore no data is illustrated. It is probable that the extent of the sampling grid did not adequately account for the rapid dispersion and the majority of the tracer sand was dispersed offshore in suspension. The disturbance recorded in the vertical sand cores indicated that between 9.5 and 10 cm of the core had been removed (figure 9:3). The coloured sand in the cores was replaced by a layer of coarse pebbles that was 6-8 cm thick. Therefore, there was a net loss in the height of the core by 3-4 cm since the time of deployment. A significant correlation was made between the disturbance of the vertical cores and an increase in the wind speed and the wave height (figure 9:2).

SAND TRACER EXPERIMENT 1

During tides 1 and 2 in experiment one the winds were light 5-8 mph, blowing onshore from a south-southeast direction. Therefore, the wave approach angle was normal to the shore. Despite the calm winds, the waves were long period swell waves with a root mean squared wave height of 0.63 metres. In these wave conditions the fluorescent tracer sand remained undisturbed in the deployment trench and an onshore transport of sand as opposed to a longshore transport occurred. The vertical sand cores highlighted that up to as much as 8 cm of fresh sand was deposited as a layer above the intact sand cores (figure 9:5a). The thickness of the deposited fresh sand in the cores increased with distance up the foreshore, as the sand was transported to the limit of the swash in suspension. The tracer pebbles were restricted from undergoing longshore transport as the onshore transport of the sand buried the pebbles further into the beach face (plate 9:4).

By tide three in experiment one the wave energy had increased. In the morning the southeast wind speeds reached 8-10 mph, the root mean squared wave breaking height was 0.44 metres and the southeast waves approached at an oblique angle of 15 degrees to the shoreline. The tracer sand dispersion illustrated an on-offshore dispersal trend furthermore, the tracer sand was dispersed either side of the deployment site in the longshore direction (figure 9:3a). The longshore transport to the southwest was up to a maximum of 75 metres in one tide. A lower concentration was displaced up to 55 metres from the deployment site to the northeast. The response of pebbles and sand were compared when subject to the same wave conditions (figure 9:6). The dispersion of the sand covered a much greater proportion of the sample grid either side of the deployment site in one tide. In contrast, the pebbles were transported in only one longshore direction to the southwest and the indigenous sandstone and ironstone tracer pebbles were relocated less than one metre from the deployment site.

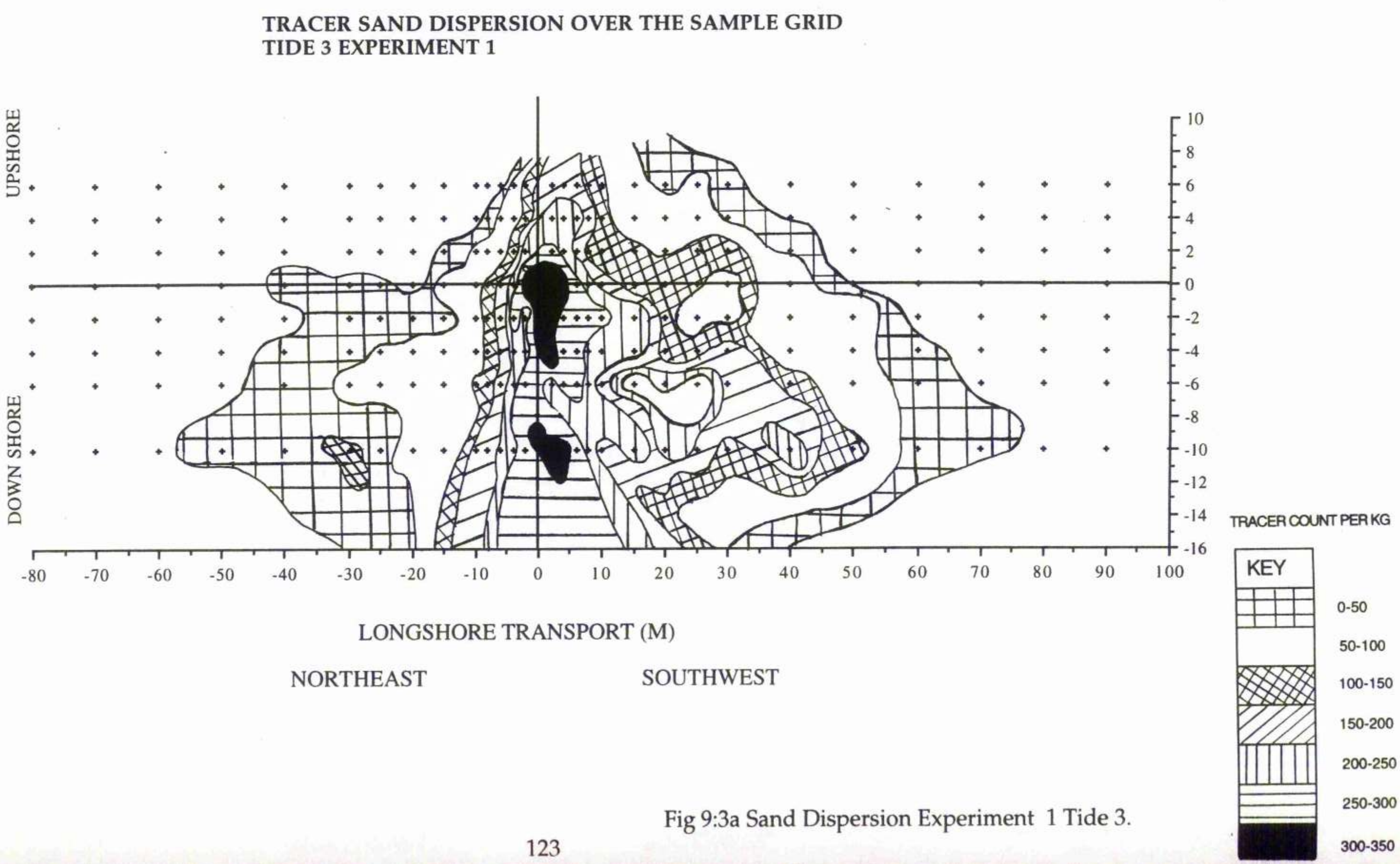


Fig 9:3a Sand Dispersion Experiment 1 Tide 3.

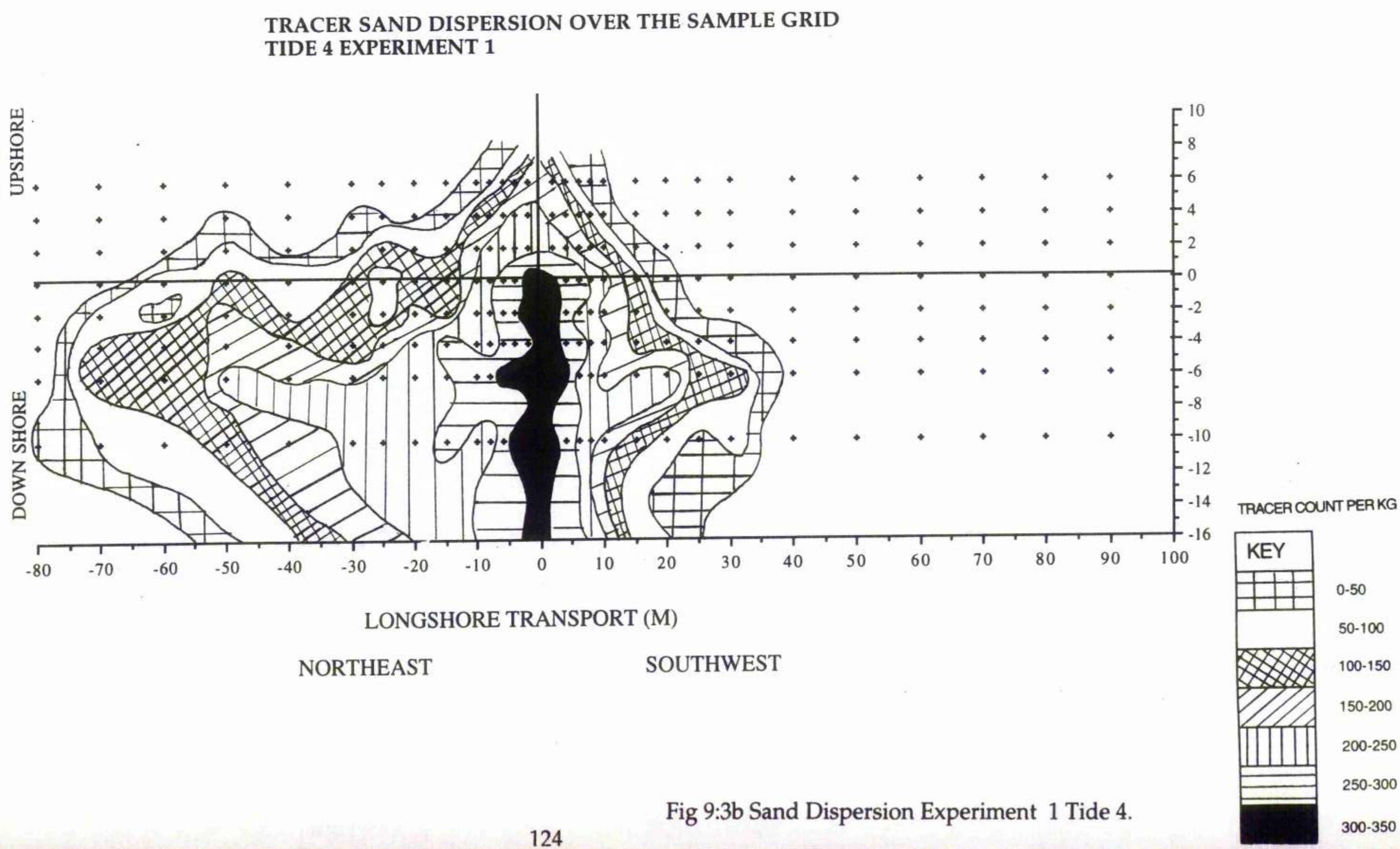


Fig 9:3b Sand Dispersion Experiment 1 Tide 4.

EXPERIMENT ONE

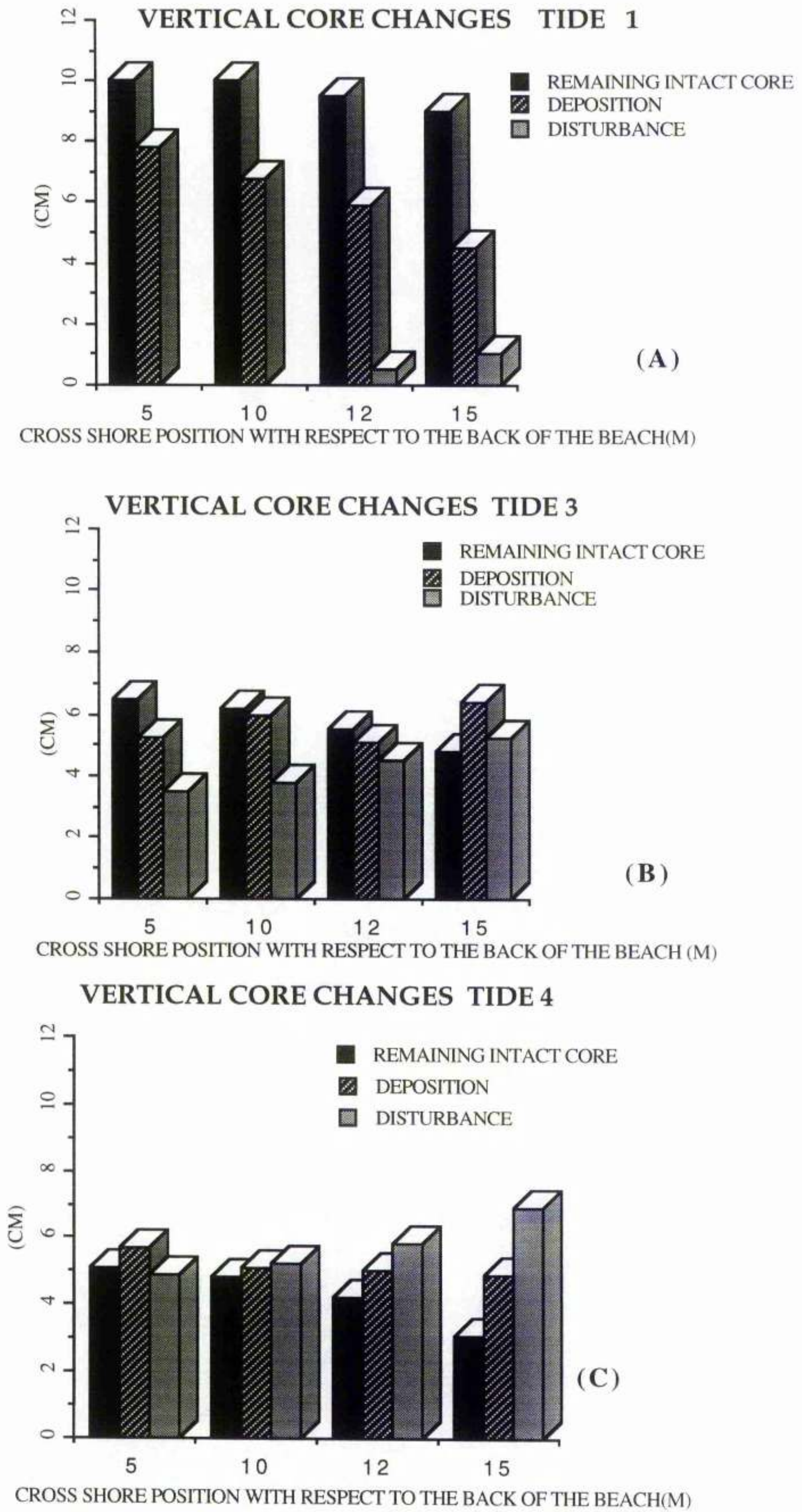
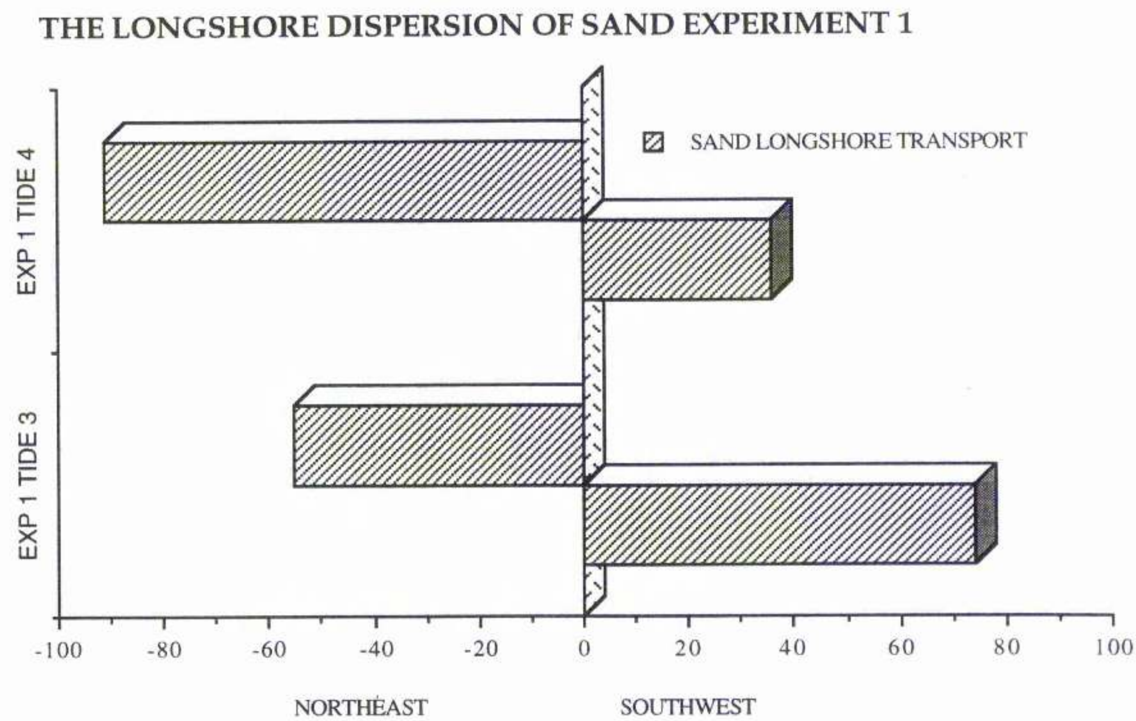


Fig 9:5 a-c Disturbance of the mixed beach
with a high proportion of sand Experiment1



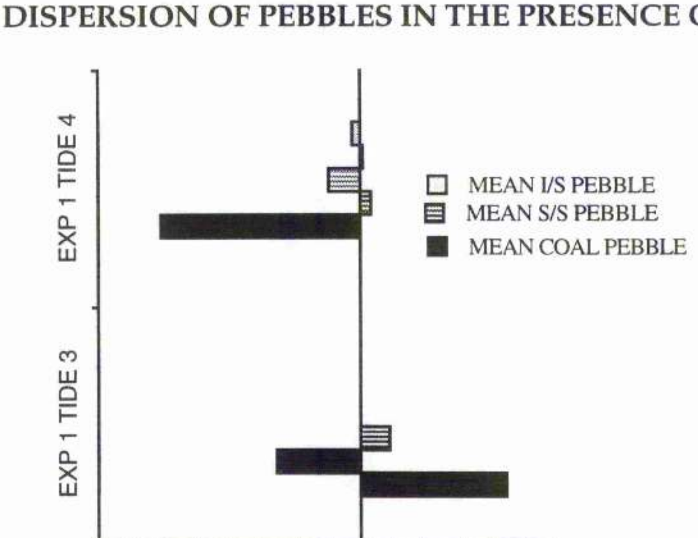


Fig 9:6 The response of pebbles in the presence of sand experiment 1.

In the afternoon, the winds reversed and blew from the southwest. The wind speeds increased to 12 mph and the wave heights recorded were between 0.45 and 0.50 metres. As a result of the change in the wave parameters the longshore sand tracer dispersion after tide 4 was predominantly to the northeast (figure 9:3b). The tracer sand was highly mobile and was dispersed up to 100 metres to the northeast and 50 metres to the southwest in one tide. Despite being subjected to the same wave conditions the indigenous sandstone and ironstone tracer pebbles displayed a sharp contrast in the rate and direction of transport in comparison to the tracer sand. In the presence of sand, the transport of the sandstone and ironstone pebbles were restricted to 1 metre northeast of the deployment site in one tide. Whereas, the mean coal pebble transport was up to 6.5 metres in one tide (figure 9:6).

The changes recorded in the vertical sand cores correlated to the wave parameters. After tide three, 5.5 cm of disturbance was recorded in the sand cores, and the layer of fresh sand deposited was up to 6.4 cm thick (figure 9:5b). The fresh deposition exceeded the disturbance on the upper foreshore. Whereas, after tide 4 the vertical cores recorded up to 7 cm disturbance which exceeded the fresh deposition (figure 9:5c). The reversal in the wind direction reworked the vertical sand cores and the thickness of sand in motion changed over time, as the wave height and wind speeds increased (figure 9:4).

SAND TRACER EXPERIMENT 2

In experiment two winds from the east reached speeds of 12-14 mph. The root mean squared wave breaking height was 0.57 metres and the waves approached from the southeast. In one tide the tracer sand was rapidly dispersed either side of the deployment site, up to a maximum of 95 metres to the southwest. An offshore trend in the tracer sand distribution was also identified (figure 9:4a). The vertical sand cores recorded up to 7.2 cm disturbance which exceeded the fresh deposition by as much as 2 cm (figure 9:7a).

By tide 2 the wave angle of the east-southeast waves was 35 degrees. The plunging waves reached heights of 0.68 metres, consequently the tracer sand recoveries were low. The dispersion of the tracer sand in the longshore direction was to the southwest. The offshore trend of sand dispersion became more significant than the longshore sand dispersion as the wave energy increased (figure 9:4b). As the sand was removed from the foreshore the rate of transport of the tracer pebbles increased by approximately 1.5 metres in one tide. The tracer pebbles were only transported alongshore in the direction corresponding to the dominant wave direction, whereas the sand was dispersed either side of the deployment site (figure 9:8). The vertical sand cores highlighted that up to 9 cm of sand was removed from the intact cores and a 5 cm layer of coarser pebbles was deposited (figure 9:7b).

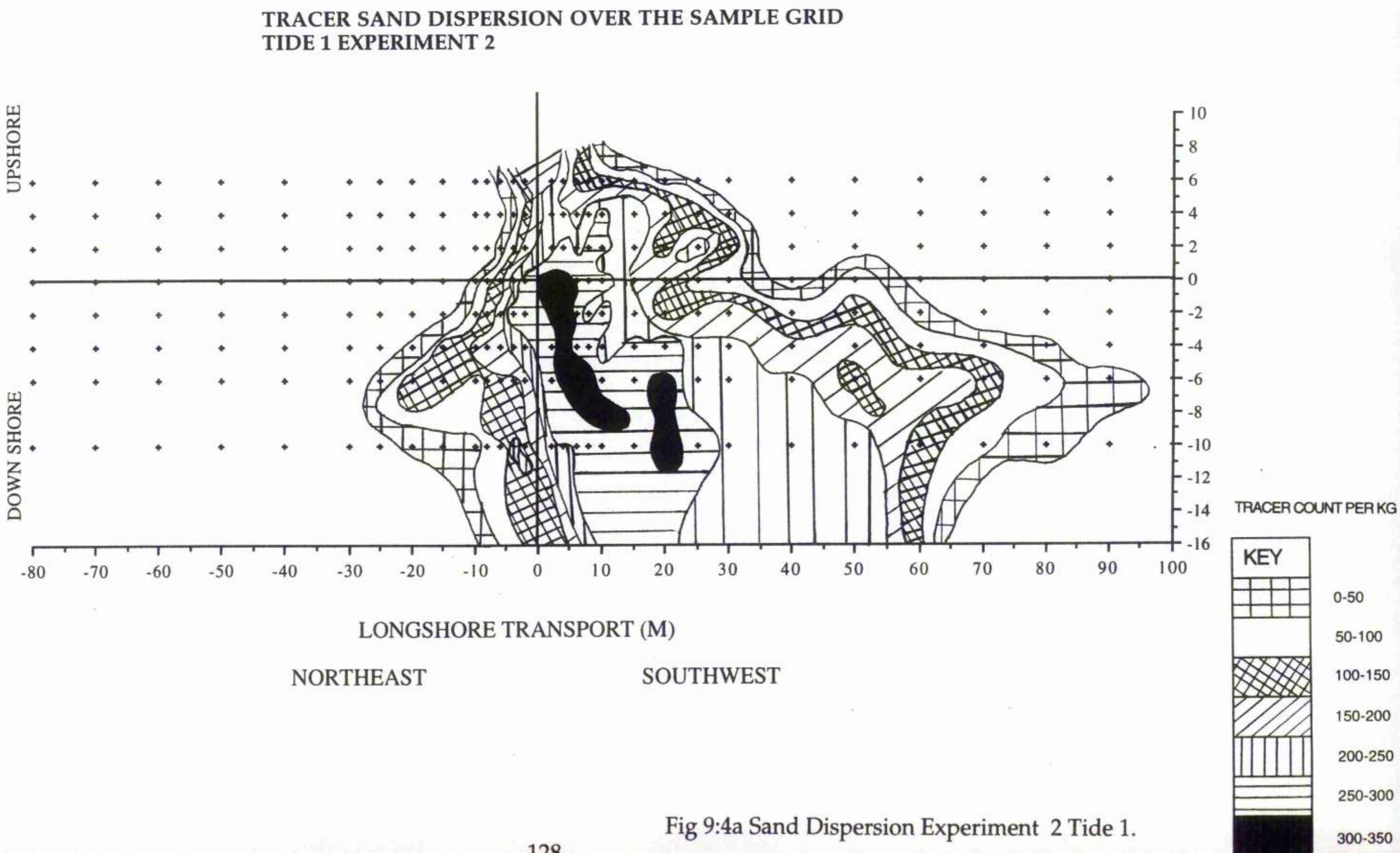


Fig 9:4a Sand Dispersion Experiment 2 Tide 1.

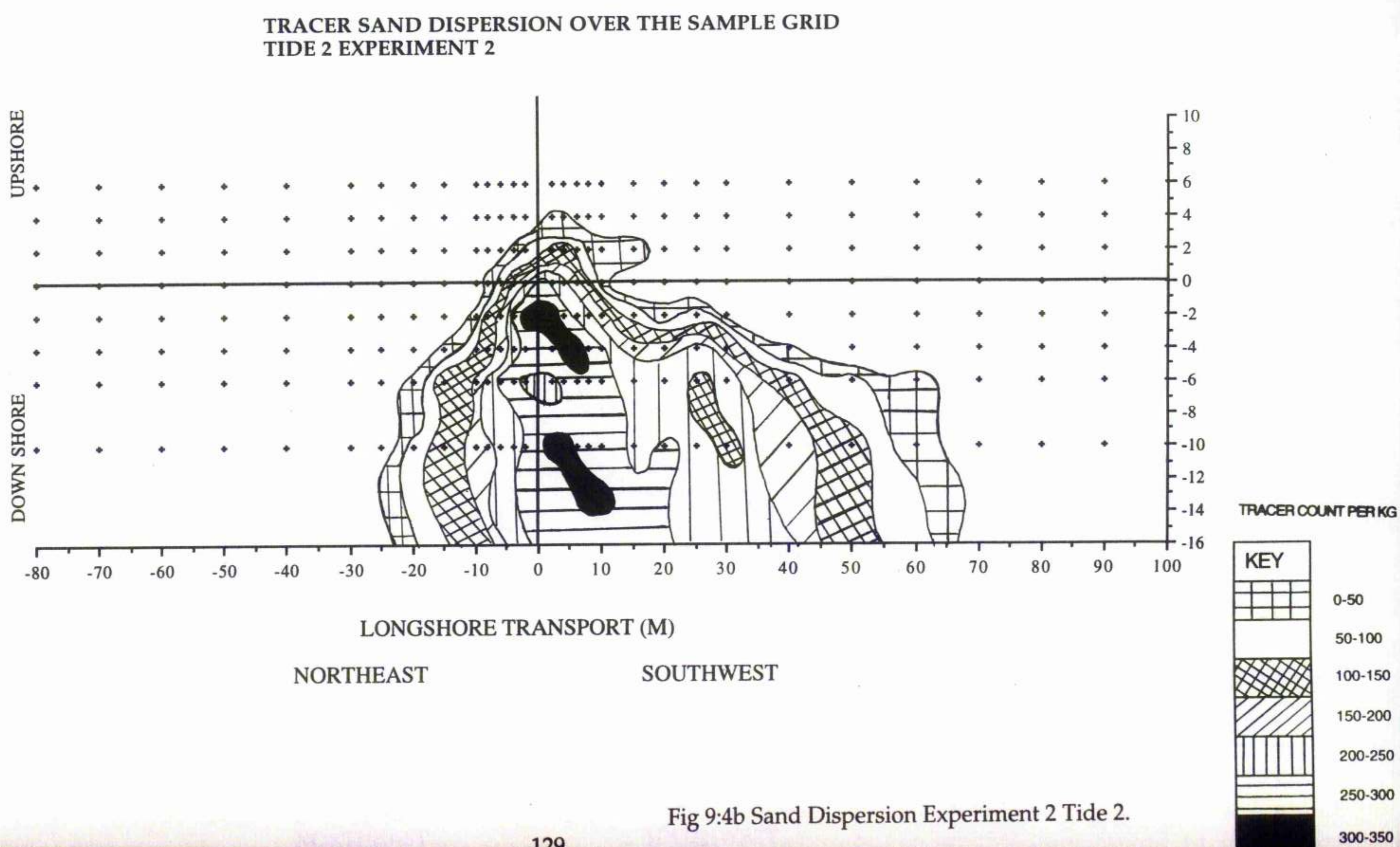
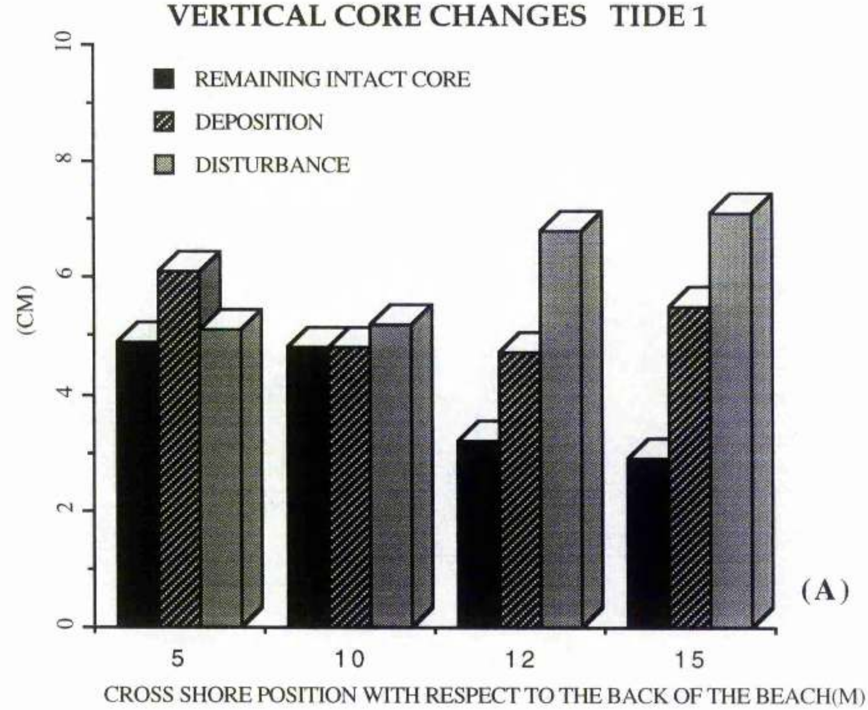


Fig 9:4b Sand Dispersion Experiment 2 Tide 2.

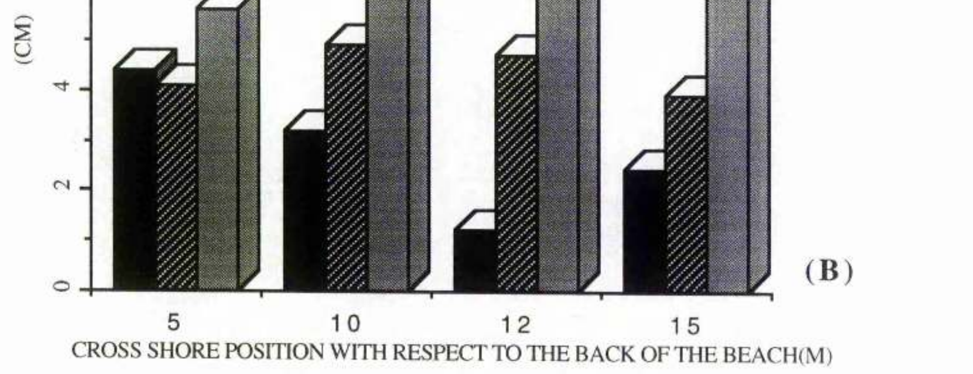
EXPERIMENT 2

VERTICAL CORE CHANGES TIDE 1



(A)

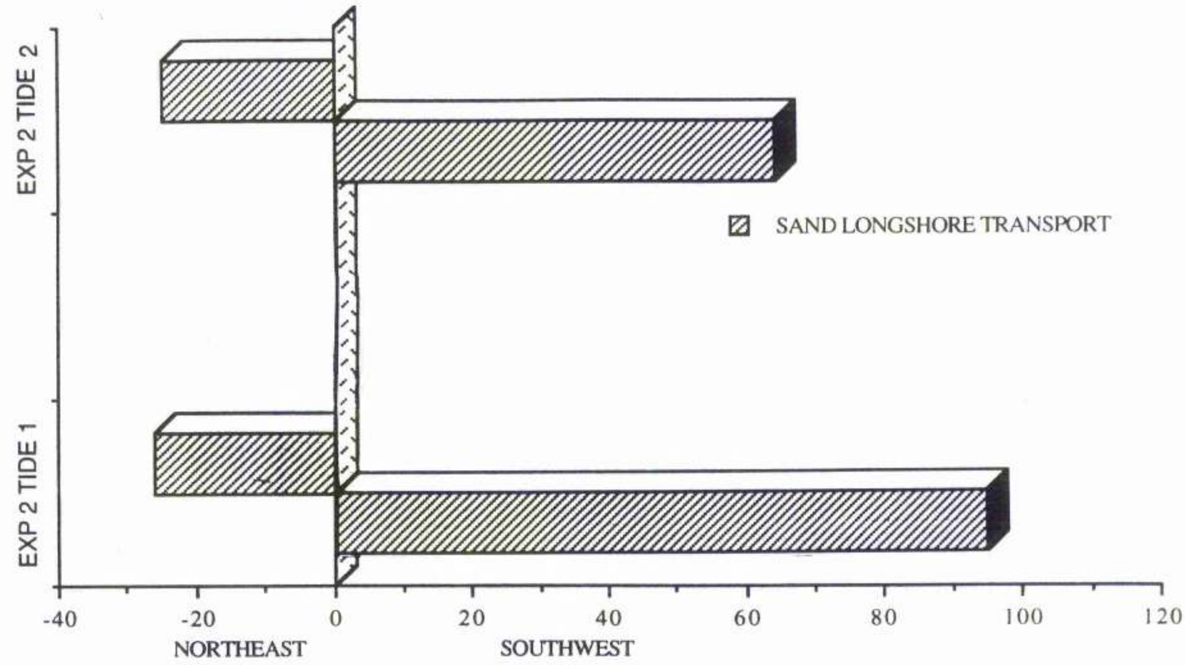
VERTICAL CORE CHANGES TIDE 2



(B)

Fig 9:7a-c Disturbance of the mixed beach with a high proportion of sand Experiment 2

THE LONGSHORE DISPERSION OF SAND EXPERIMENT 2



DISPERSION OF PEBBLES IN THE PRESENCE OF SAND

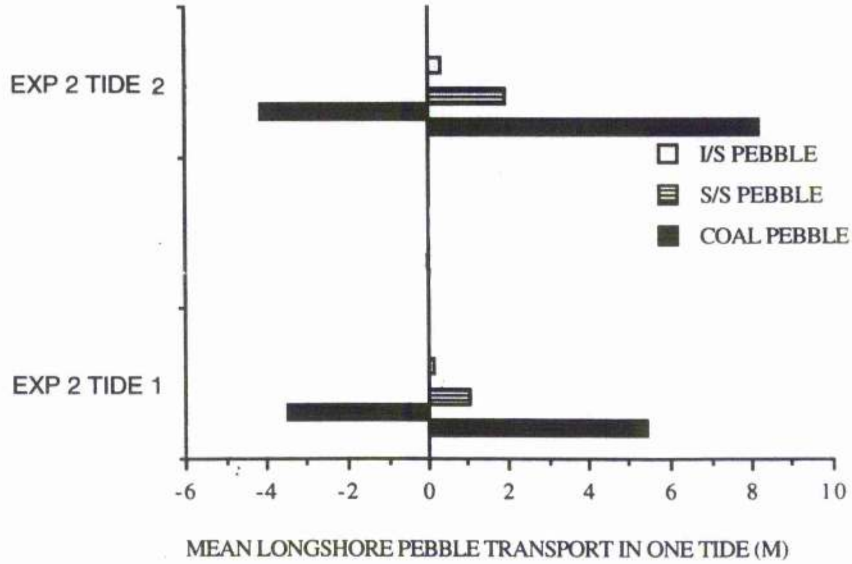


Fig 9:8 The response of pebbles in the presence of sand experiment 2.

When a high proportion of sand composed the mixed beach, the tracer pebbles that were buried by the overlying sand were restricted in their longshore transport (figure 9:9) (plate 9:4). Even the longshore transport of the coal pebbles buried in the sand was limited. When low wave energy conditions prevailed the buried ironstone tracer pebbles underwent no transport with an increase in the wave energy the mean transport rate was only 0.25 metres in one tide. Whereas, the mean transport of ironstone tracer pebbles when sand was not present on the mixed foreshore was 0.88 metres in one tide. Observations indicated that the dense ironstone pebbles had a tendency of becoming buried in the sand and generated dispersive pressures which put sand in motion. Small rills were evident below the protruding pebbles that ran down the beach slope. The sand was preferentially transported around the dense pebbles burying them further into the sand. In low wave energy conditions the mean transport of the sandstone pebbles when sand was absent from the mixed beach was 2.3 metres. When the sandstone tracer pebbles were partially buried in the sand the mean longshore transport was 1.8 metres in one tide, this longshore transport decreased to less than 1 metre when the sandstone tracers were entirely buried in the sand. Even as the wave energy increased the presence of sand on the mixed foreshore restricted the longshore transport of the buried sandstone and ironstone pebbles. For example in moderate wave energy conditions, the mean transport of the sandstone pebbles without sand was 4 metres. However, when these pebbles were buried by sand on the mixed beach the mean longshore transport in one tide was reduced to 2.5 metres. As the wave energy increased, observations revealed that the coal pebbles behaved similarly to the sand and were carried in suspension offshore.

The cross shore transport of pebbles on the mixed beach with a high proportion of sand was compared to the situation when sand was absent from the surface of the mixed beach (figure 9:10). When sand was absent from the mixed beach the mean transport upshore for the sandstone tracers was 2 metres in one tide. Whereas, when sand was present on the mixed beach the mean upshore transport increased to approximately 5 metres in one tide. Similarly, the mean cross shore transport of the ironstone pebbles increased from less than 1 metre to approximately 4 metres in one tide.

Consequently, when sand composed a high proportion of the mixed foreshore the cross shore transport of the indigenous sandstone and ironstone pebbles was more significant than when pebbles dominated the surface of the mixed beach.

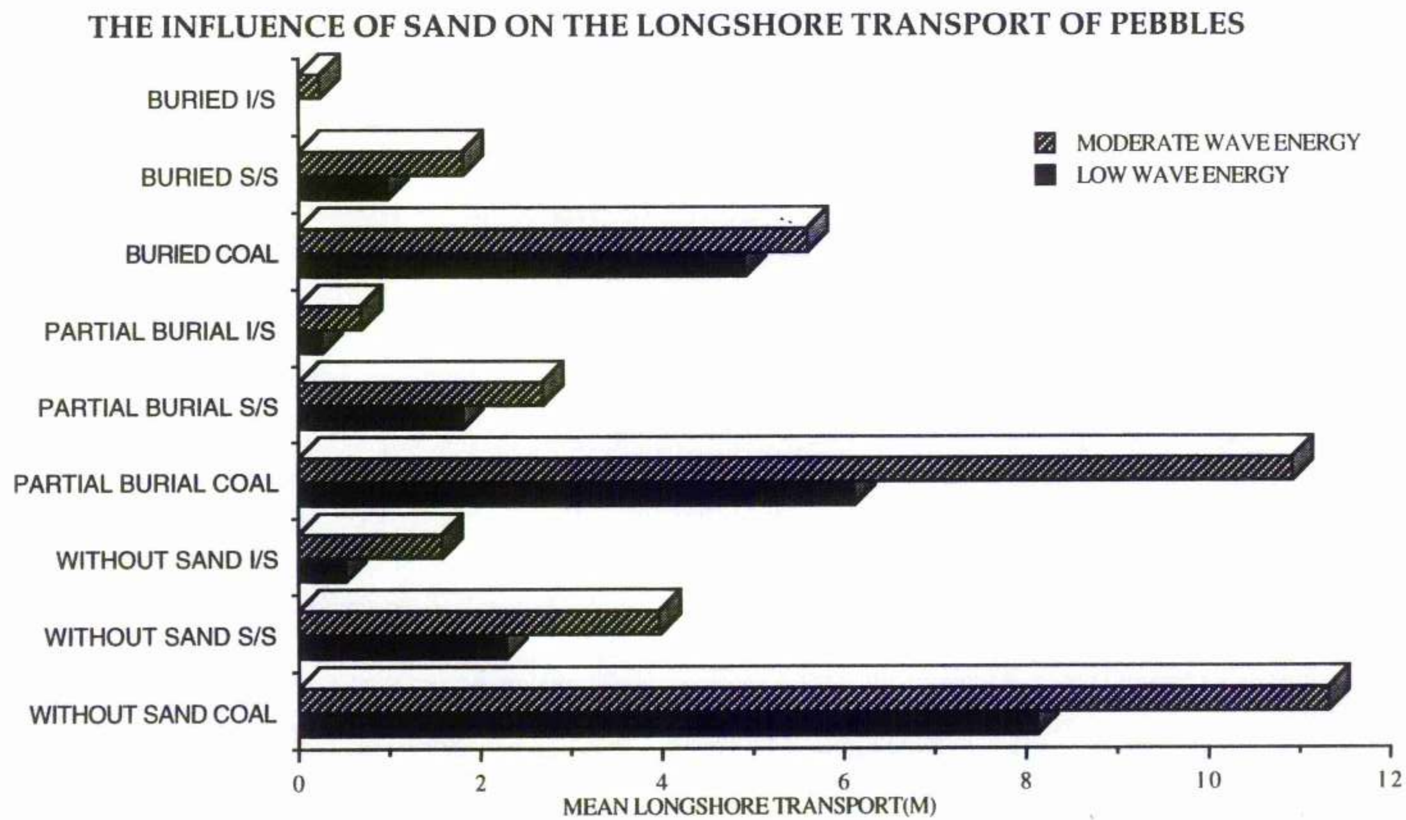
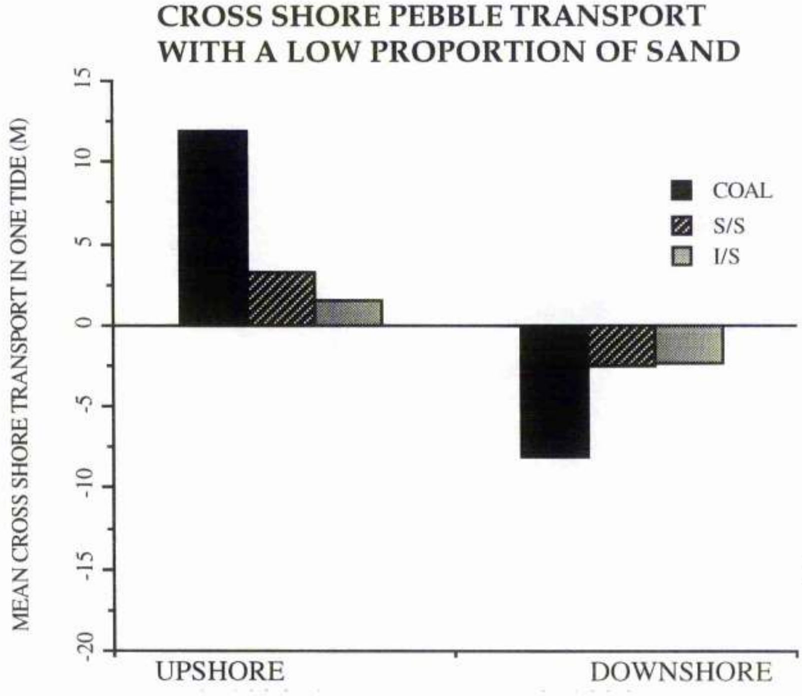
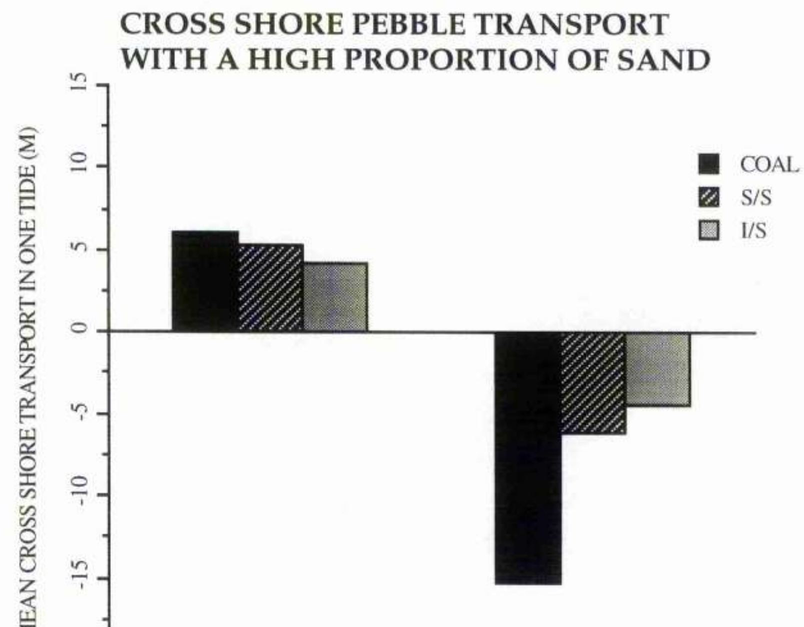


Fig 9:9 The response of pebbles in the presence of sand.



(A)



(B)

Fig 9:10 Cross shore pebble transport
according to the proportion of sand on the mixed beach.

9:13 DISCUSSION THE RESPONSE OF SAND ON A MIXED BEACH

When subjected to the same wave conditions the tracer sand and pebbles moved in opposite directions and at different rates. Furthermore, the proportion of the sand on the mixed beach face caused the longshore transport rates of the pebbles to fluctuate. The dispersion of the tracer sand and the disturbance of the sand cores correlated to the wave conditions. In low wave energy conditions, the sand was highly mobile, whereas the coarse pebbles were buried deeper by sand that was transported onshore. As the angle of the breaking waves became more significant the sand was moved in the backwash, then dispersed rapidly by tidal and longshore currents either side of the deployment site. The tracer pebble transport only took place in the direction of high wave energy, controlled by the swash and backwash of the breaking waves, with the exception of certain coal pebbles that were transported in suspension with the sand. Furthermore, the presence of sand on the mixed beach influenced the response of pebbles in wave action. The sand encouraged the transport of pebbles upshore by rolling and sliding, to create pebble bands at the swash limit. The response of pebbles in the presence of sand supported the model of Jackson and Nordstrom 1993 (figure 9:11).

When the wave heights increased the greater disturbance of the beach face caused the sand to be transported offshore in the backwash to leave a mobile layer of better sorted pebbles and the longshore transport of the pebbles increased. The remaining sand on the mixed beach was transported to depth to create an interstitial component between the pebbles.

In conclusion, when a high proportion of sand composed the mixed beach the longshore transport of the pebbles was restricted and the poor sorting of the pebbles and sand reduced the thickness of the moving layer of sediment undergoing longshore transport (section 10:1). Consequently, renourishing beaches with a mix of sand and shingle could provide a method of increasing beach stability. This concept is reviewed in the final chapter.

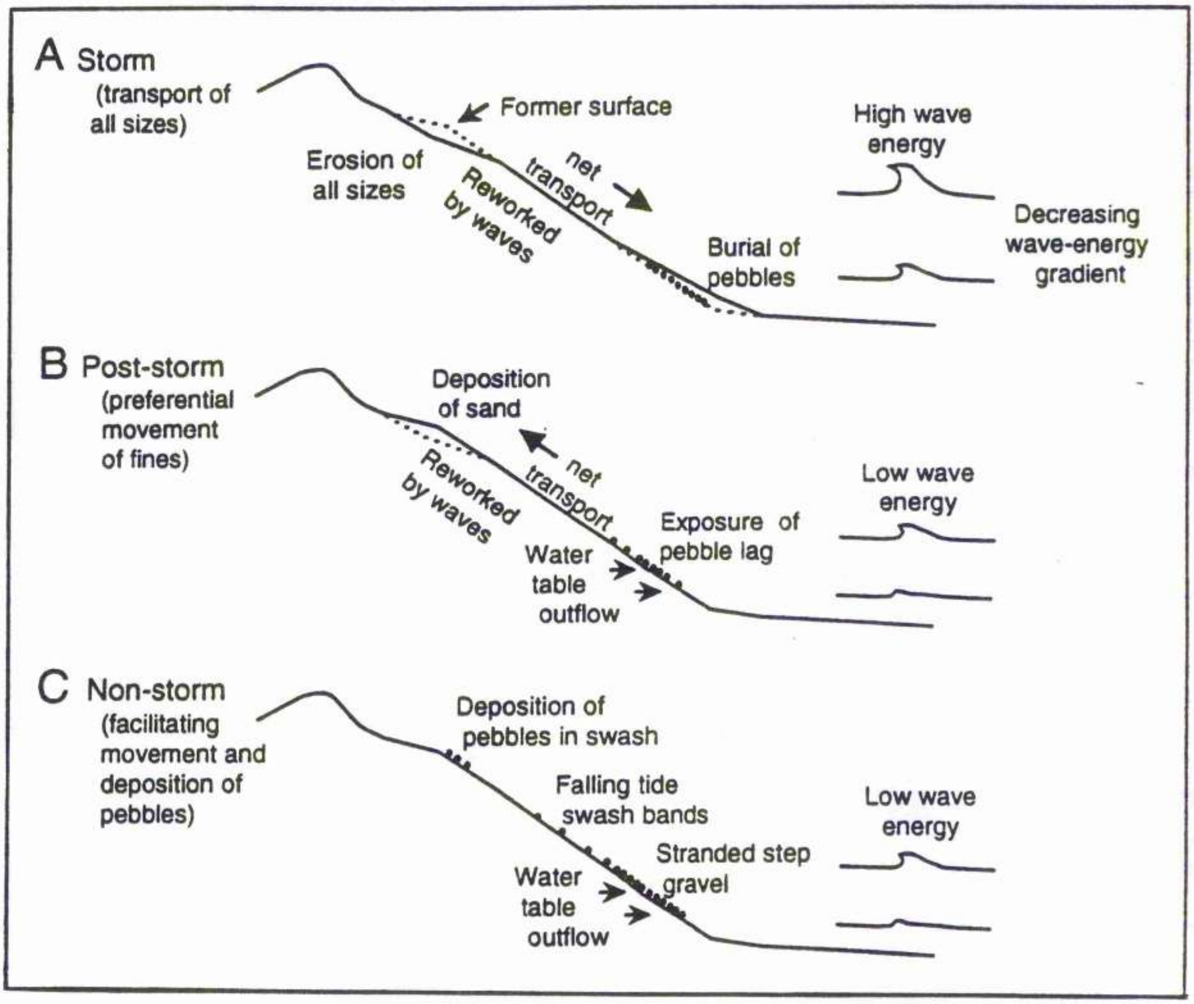


Fig 9:11 Jackson and Nordstrom Model(1993) of the response of pebbles in the presence of sand in a tidal estuarine setting.

10:1 VERTICAL BEACH PROFILES

After investigating the transport behaviour of the sand that can overlie the pebbles on the mixed beach and the changes in the vertical sand and pebble cores, it was apparent that the transport processes on the mixed beach were influenced by the sedimentary structure of the beach face. However, the literature on the sedimentary structure of vertical beach profiles was very limited. The examination of the vertical beach cores by Wright and Nicholls (1985) at Hengistbury Head was of particular interest to this research. The findings revealed that the sedimentary organisation of the vertical beach face was dependent on the wave conditions. In swell conditions the build up of the beach destroyed the pre-existing sorting in the vertical beach cores, whereas storm waves combed down the beach face. Isla (1993) identified that pebbles and sand were segregated at depth in the beach face. Round coarse pebbles armoured the beach surface, whereas finer sediments were selectively removed or deposited lower in the beach profile. The majority of the other literature reviewed, focused on ancient beach profiles preserved in sedimentary sequences. A series of contrasting vertical beach facies consisting of laminated sands and pebbles were identified from the lower to upper shoreface. The facies were interpreted in the light of beach processes operating today by various researchers Massari and Parea (1988), Hart and Plint (1989) and Postma and Nemec (1990). As this mixed beach similarly consists of laminated sands and pebbles, a short experiment was proposed to examine the vertical profiles on this mixed beach. Many of the interpretations made to account for the sedimentary organisation of the ancient beach profiles were found to be relevant.

Objectives;

1-To investigate the composition and vertical structural organisation of the beach face, in particular the distribution of sand and pebbles.

2-To assess the cross and longshore variations in the vertical profiles.

3-To assess the impact of varying wave and tidal changes on the composition and structure of the vertical beach face.

METHODS

To assess the spatial variations in the vertical beach profiles trenches were excavated to 50 cm from the lower and upper foreshore, at three transects positioned alongshore (figure 5:3). Trenches were repeatedly excavated at the same sites to compare the structure and composition of the vertical profiles over time. When sand was present amongst the pebbles, the beach profile was stable. However if the trench was dug in loose pebbles the vertical face of the trench was prone to collapse. Therefore, a new technique was applied to gain insight into the vertical structure of mixed beaches.

FREEZE CORE SAMPLER

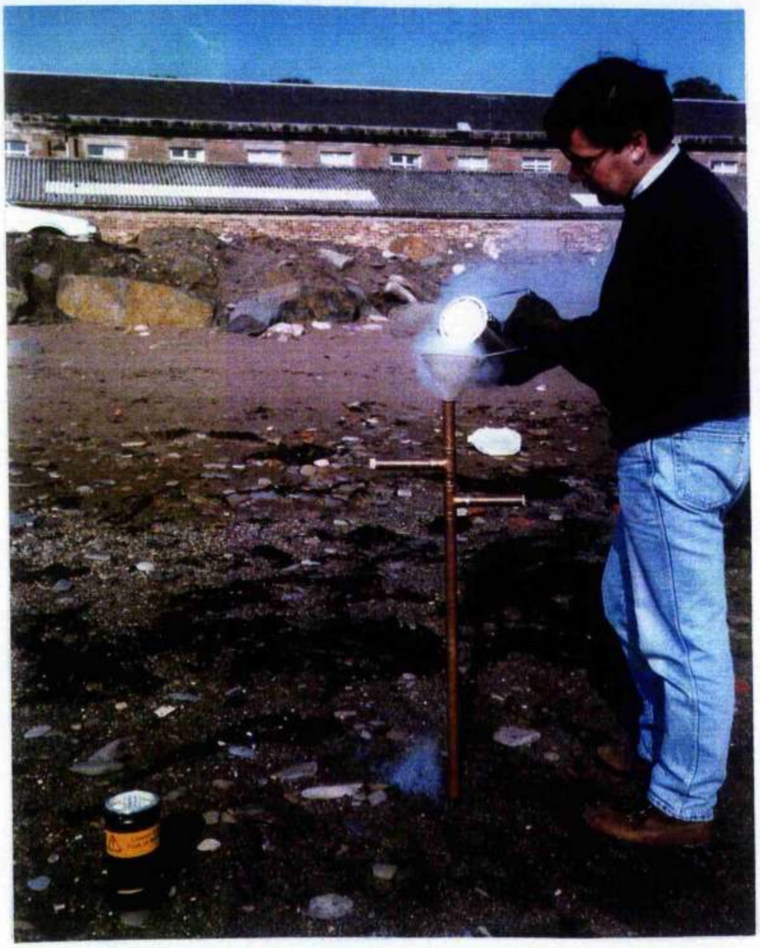
Freeze core sampling has previously been used to investigate the vertical structure of coarse river beds (Carling 1981). Vertical cores were obtained by inserting a pipe into the river bed. A freezing agent was poured down the pipe and the saturated or partially saturated river substratum was frozen to the pipe. When the pipe was extracted the freeze sampling technique produced an undisturbed and precisely oriented volumetric vertical sample of the bed. The vertical core retained the fine matrix and primary structure of the beach face. It was therefore proposed that this technique would be attempted on the mixed beach.

A freeze core sampler was constructed, with amendments to the initial design of (Carling and Crompton 1988). The freeze core sampler consisted of a hollow copper stand pipe, 1.5 metres in length which had a 28 mm external diameter. At the top of the vertical stand pipe there were two much shorter horizontal pipe sections with bungs placed at each end. The pipe had a pointed base to enable it to be driven into the beach face.

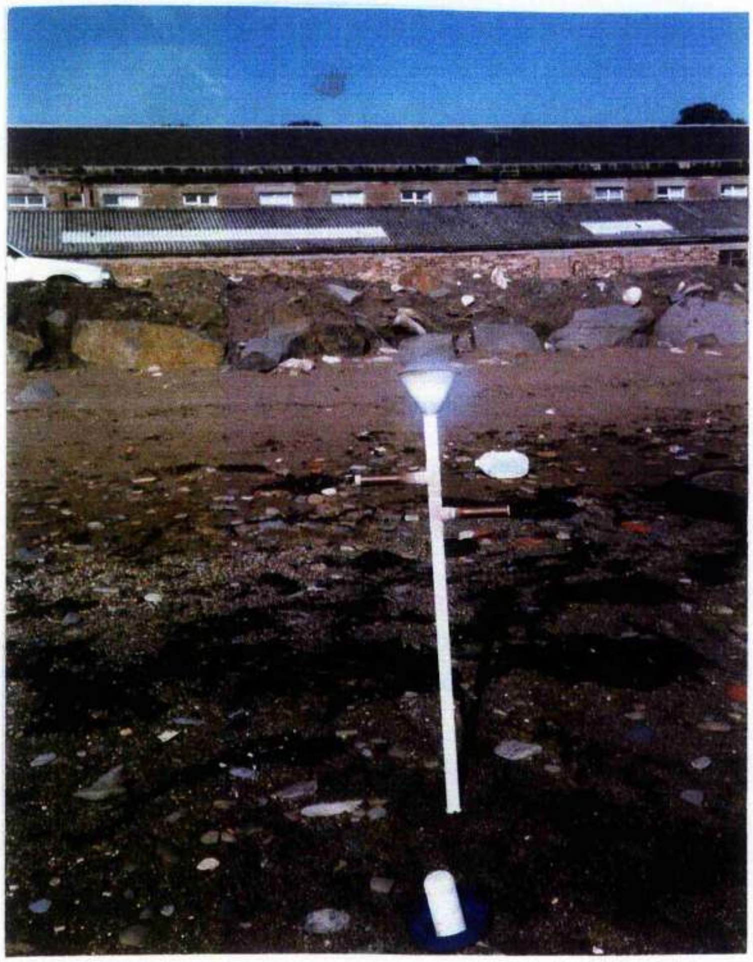
An experiment was undertaken using liquid carbon dioxide as the freezing agent. A brass manifold tube with a 10 mm external diameter was inserted into the stand pipe. The manifold tube had fine nozzles of 1.45 mm diameter to regulate the release of the freezing agent into the lower portion of the stand pipe (figure 10:1). The liquid carbon dioxide was fed into the manifold tube from a 10 kg cylinder via a pressure hose that was fitted with a regulator. This induced a rapid pressure drop and the subsequent vaporisation of carbon dioxide. Solid carbon dioxide appeared as snow at the top of the stand pipe confirming that freezing had taken place. Although the method successfully produced a vertical core of beach sediment, the quantity of liquid carbon dioxide required to produce a vertical core would be impractical in the beach environment. The method was also hazardous as freezing caused the build up of pressure in the hose and it shattered explosively.

With slight modification a successful and safe method was developed. Liquid nitrogen was used as the freezing agent which was cheaper, safer and more easily transported in a large gyre container. The manifold tube was no longer required, once the stand pipe had been inserted into the beach face the liquid nitrogen was poured down the stand pipe with the aid of a funnel. The stand pipe was inserted into the beach face to a depth of 0.75 metres. Then a one litre container was used to pour the liquid nitrogen down a funnel into the pipe. When pouring the liquid nitrogen it was essential that all exposed skin was covered and protective gloves and goggles were worn (plates 10:1a /b).

The cores were taken following a receding tide when the foreshore was still partially saturated. The volume of liquid nitrogen required for the formation of a vertical core depended on the sediment size, bed consolidation and saturation.



(A)



(B)

Plate 10:1 Freeze core sampler (a) pouring of liquid nitrogen.
(b) frozen core for extraction.

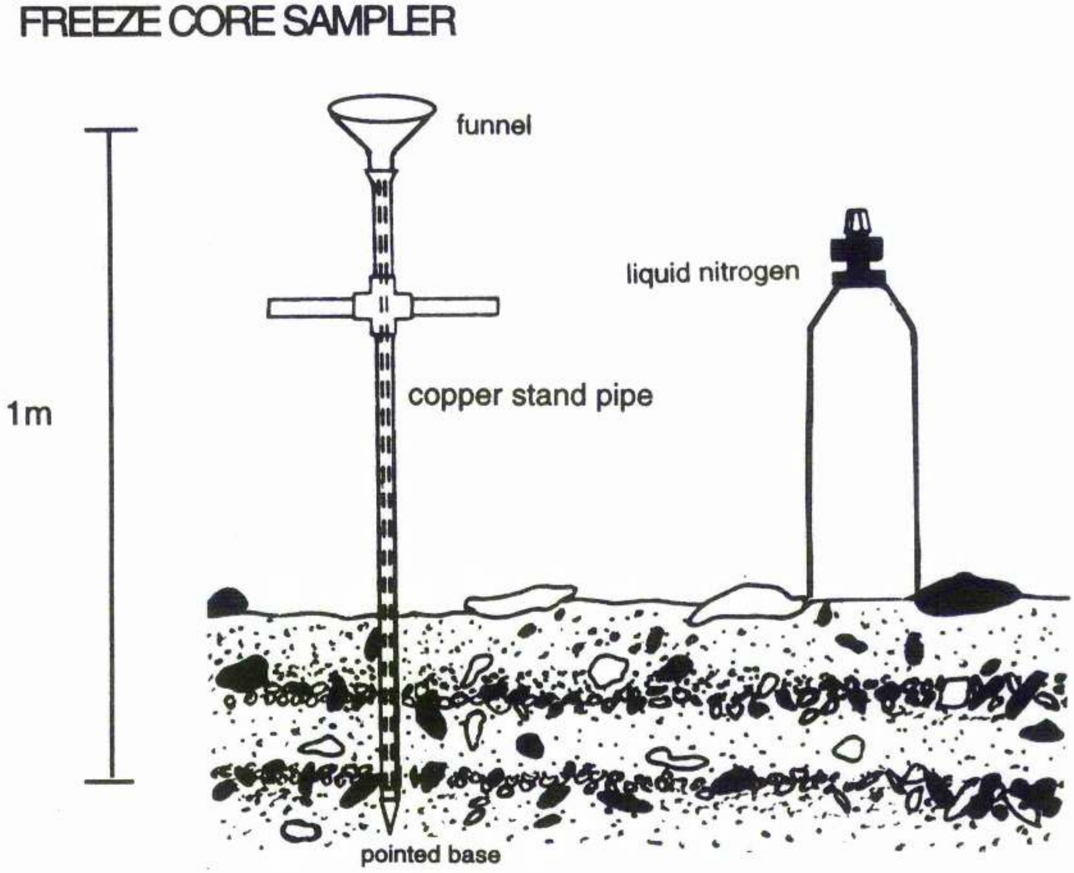


Fig 10.1 Vertical beach core freeze sampler (modified Carling and Crompton 1988).

Plate 10.2 Vertical core with mixed beach sediment attached.

Approximately four litres of liquid nitrogen were required for each core. This resulted in rapid freezing of the interstitial water, pebbles and sand particles onto the stand pipe. The vertical core sample was then obtained from the beach face by manually loosening the pipe from the surrounding sediment. If this was unsuccessful the core was dug out. Pouring hot water down the pipe helped loosen the core from the pipe. Once the core was extracted it began to melt, therefore to record the structure and composition of the core photographs and annotated records were made in the field (plate 10:2). Ideally, the cores should be placed into a container of similar diameter to maintain the structure of the core, storage in a cool box would keep the frozen core intact, whilst other core samples are taken.

10:12 RESULTS

SPATIAL AND TEMPORAL CHANGES IN THE VERTICAL STRUCTURE OF THE MIXED BEACH

The beach cores were between 15 and 20 cm in width and up to 50 cm long and effectively preserved the structure, sorting and packing of the pebbles and sand on the mixed beach. Even the largest pebbles were frozen in situ (plate10:2). Many of the vertical cores displayed diagnostic layering with segregation of the pebbles according to size, alternating with layers of sand (plate 10:3). The vertical profiles are described below and interpreted according to wave and tidal processes.

VERTICAL PROFILES CORRESPONDING TO THE SWASH ZONE

Vertical profiles taken throughout the swash zone displayed an inverse grading with the coarse pebbles positioned at the top of profile (figure 10:2). A high proportion of fine pebbles were situated below. Profiles collected in the swash zone over time had a variable thickness, size and sorting of the pebbles within the upper profile. The sorting created loosely consolidated profiles with an open permeable framework. At greater depths the profile became poorly sorted, as the pebbles were intermixed with finer pebbles. The sand was an interstitial component in the pores of the less mobile pebble framework.

INTERPRETATION

The composition and structure of the vertical profiles were attributed to wave processes operating within the swash zone. When the upper layers of the vertical profiles consisted of a thick layer of well sorted coarse pebbles with fine pebbles below, the beach cores were collected from the swash berm. The berms developed at the still stand at high water, where the swash decelerated leading to the accretion of pebbles. Vertical cores taken at the same position over time, revealed that the swash rhythmically disturbed the upper section of the vertical profiles. According to the hydraulic forces of the oncoming swash, the pre-existing structure of the vertical profiles was either maintained, reinforced or reassembled.

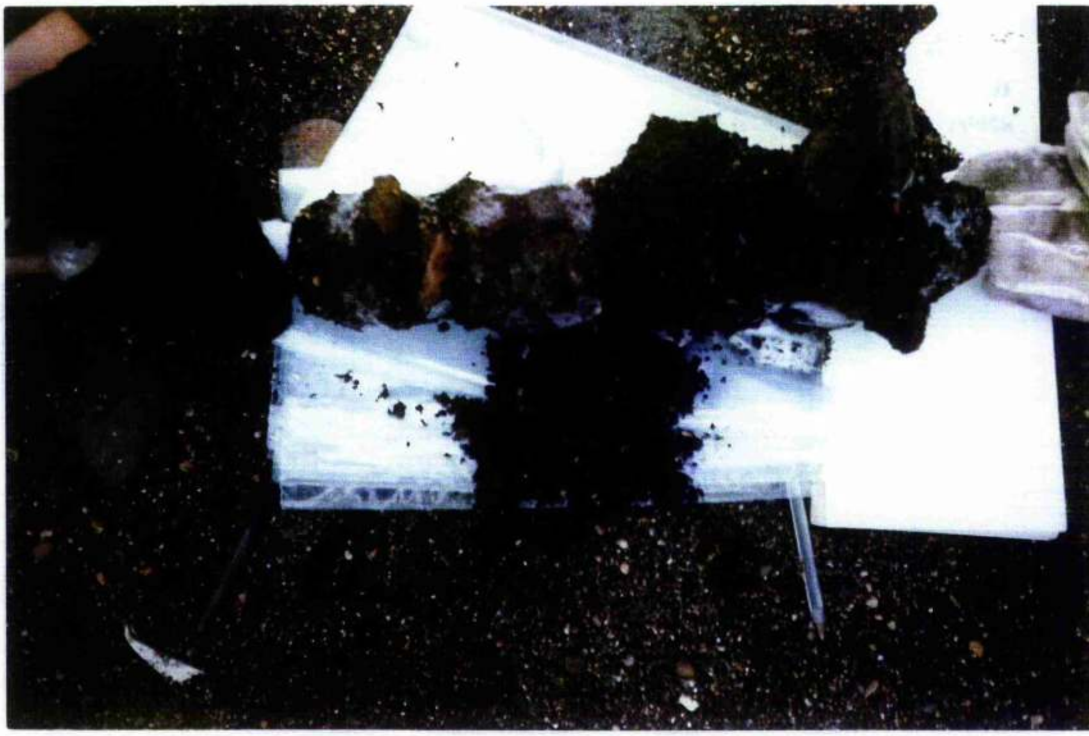


Plate 10:3 Vertical Core with interlaminated sands and pebbles.

Plate 10:4 Vertical core with dark and light sand layers.

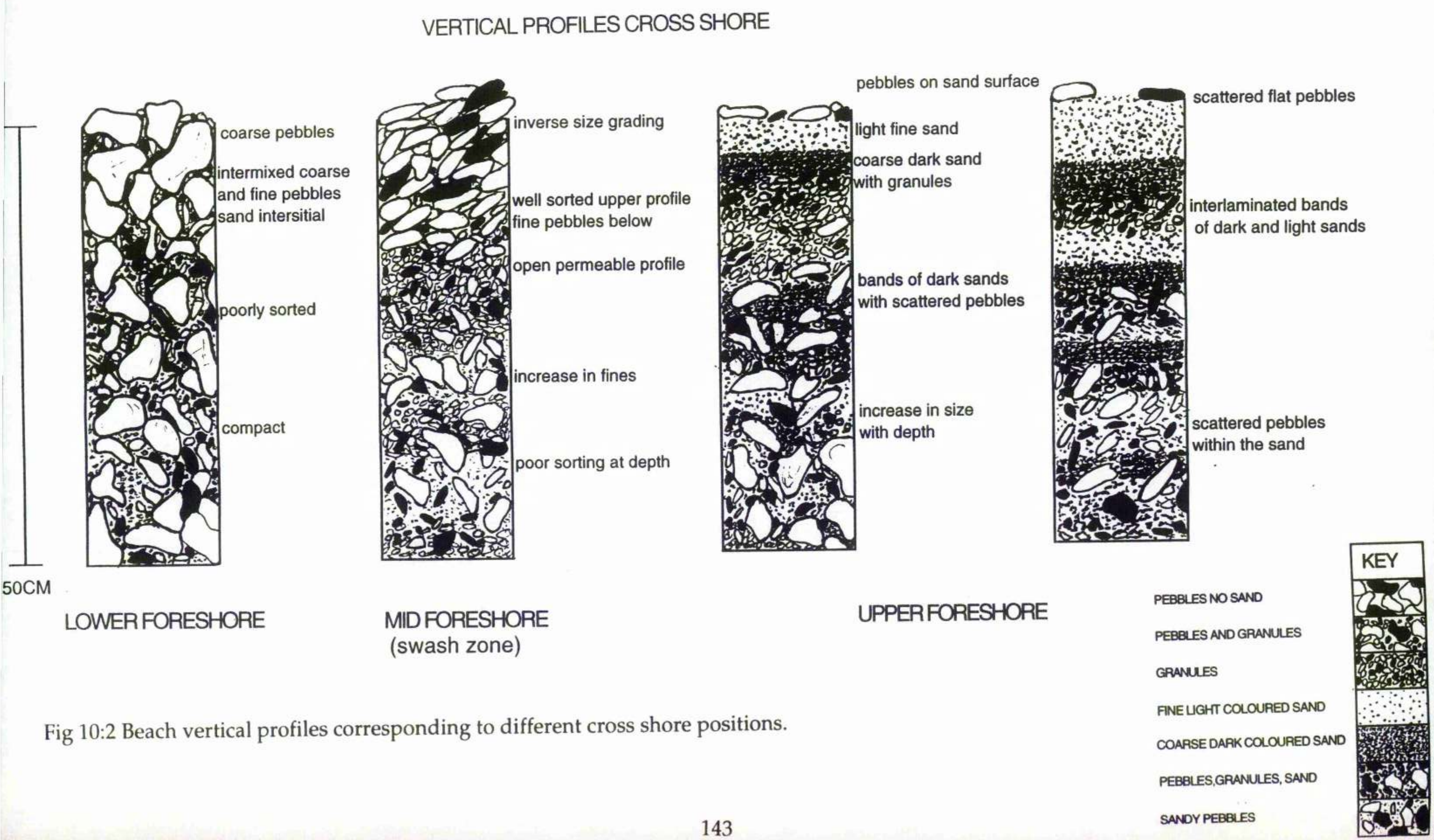


Fig 10:2 Beach vertical profiles corresponding to different cross shore positions.

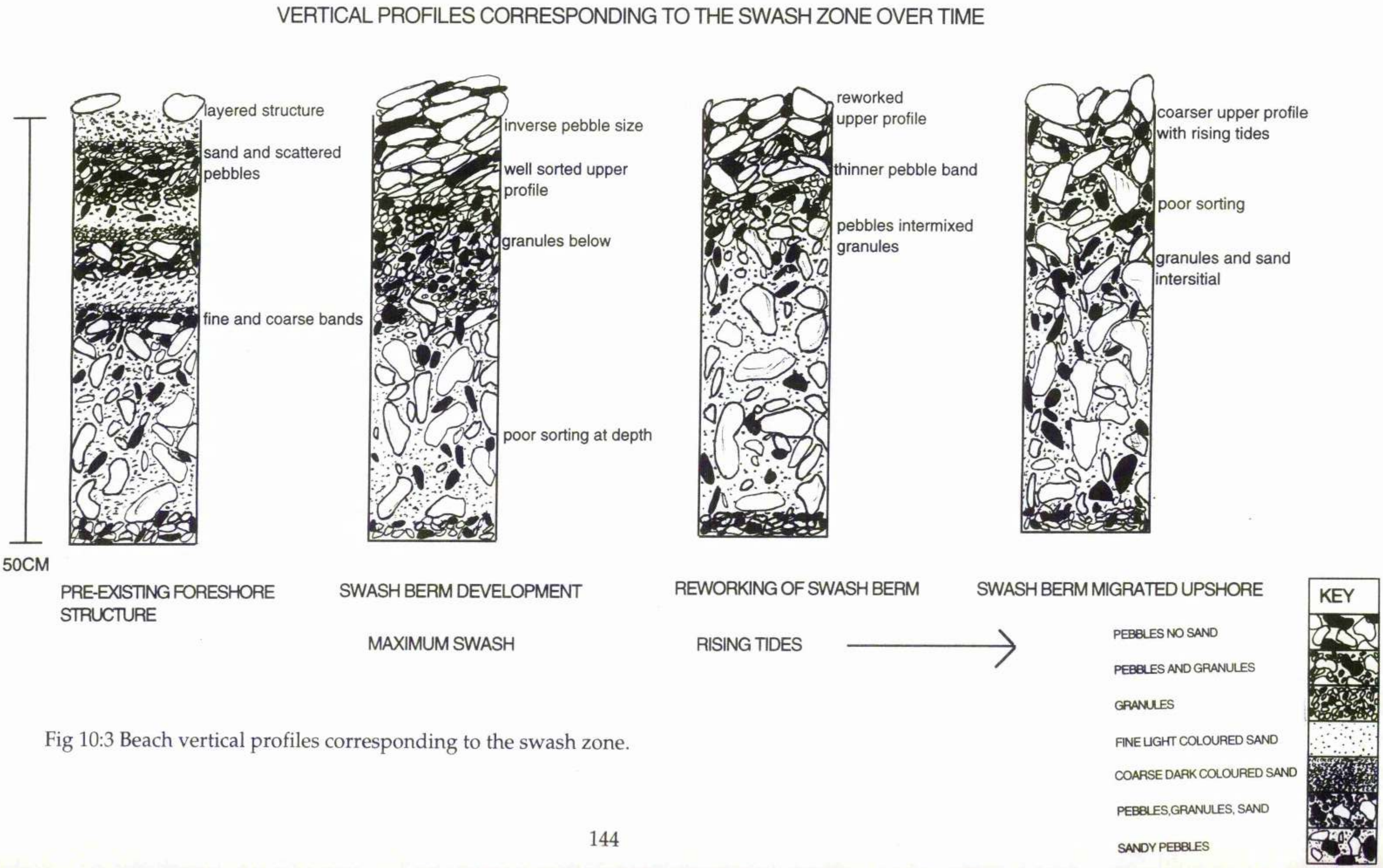


Fig 10:3 Beach vertical profiles corresponding to the swash zone.

As no two tides were the same coarser or finer pebbles of a greater or lesser volume were transported in the swash and mixed with the pre-existing sediment in the profile. When the tide level was rising the vertical profiles taken in the swash zone became coarser as the coarse and fine pebbles were remobilised and transported upshore (figure 10:3). At the position of the swash berm the vertical profile was highly permeable, the backwash was subjected to a rapid loss of energy by water percolation. Therefore, the backwash was only responsible for re-orienting small pebbles within the vertical profile.

VERTICAL PROFILES CORRESPONDING TO THE UPPER FORESHORE

On the upper foreshore of the mixed beach the vertical profiles were segregated into layers according to the size of the sediments which ranged from pebbles to sand (figure 10:2). A series of sandy layers of variable thickness were sharply bounded by fine pebble bands. These layers were gently inclined towards the lower foreshore. The vertical profiles displayed a fining upwards structure. Within the coarser pebble bands there was also a fining upwards structure. The sand was segregated into layers of different composition. A coarse dark shale rich sand, with coal waste detritus alternated with a lighter coloured quartz feldspar rich sand. Isolated larger pebbles were also found within the vertical structure.

INTERPRETATION

The vertical profiles which corresponded to the upper foreshore had up to 10 cm of sand overlying the pebbles below. An interpretation of the vertical profiles must take into account the formation of sand layers bounded by pebble rich layers. With sand and pebbles exposed near the surface, subsequent accretion of sand occurred in swell wave conditions or when the water level was particularly high. However, an increase in the wave height and wave angle was associated with the upshore and longshore movement of pebbles which buried the sand below. Alternatively, the breakdown of the storm berm at the top of the beach redistributed pebbles within the sand. The destruction of cusps would also lead to the mixing of pebbles with sands. An interesting feature in the profiles was the varying composition of the sand. Distinct light and dark sand bands were interlaminated. The darker coarser sand layers were attributed to higher wave energy events (plate 10:4). There are potentially layered offshore sand sinks, in which the darker coarser material is at greater depths than the finer quartz rich sand. The sand composition also related to the wave direction, the coarse dark coal detritus rich sands were associated with strong west winds, whereas the lighter coloured sand occurred when the wave approach was from the south southeast. The structure of the profiles collected from the upper foreshore over time indicated that the thickness of the layers were modified and fresh sand was deposited as a layer in the upper profile (figure 10:4).

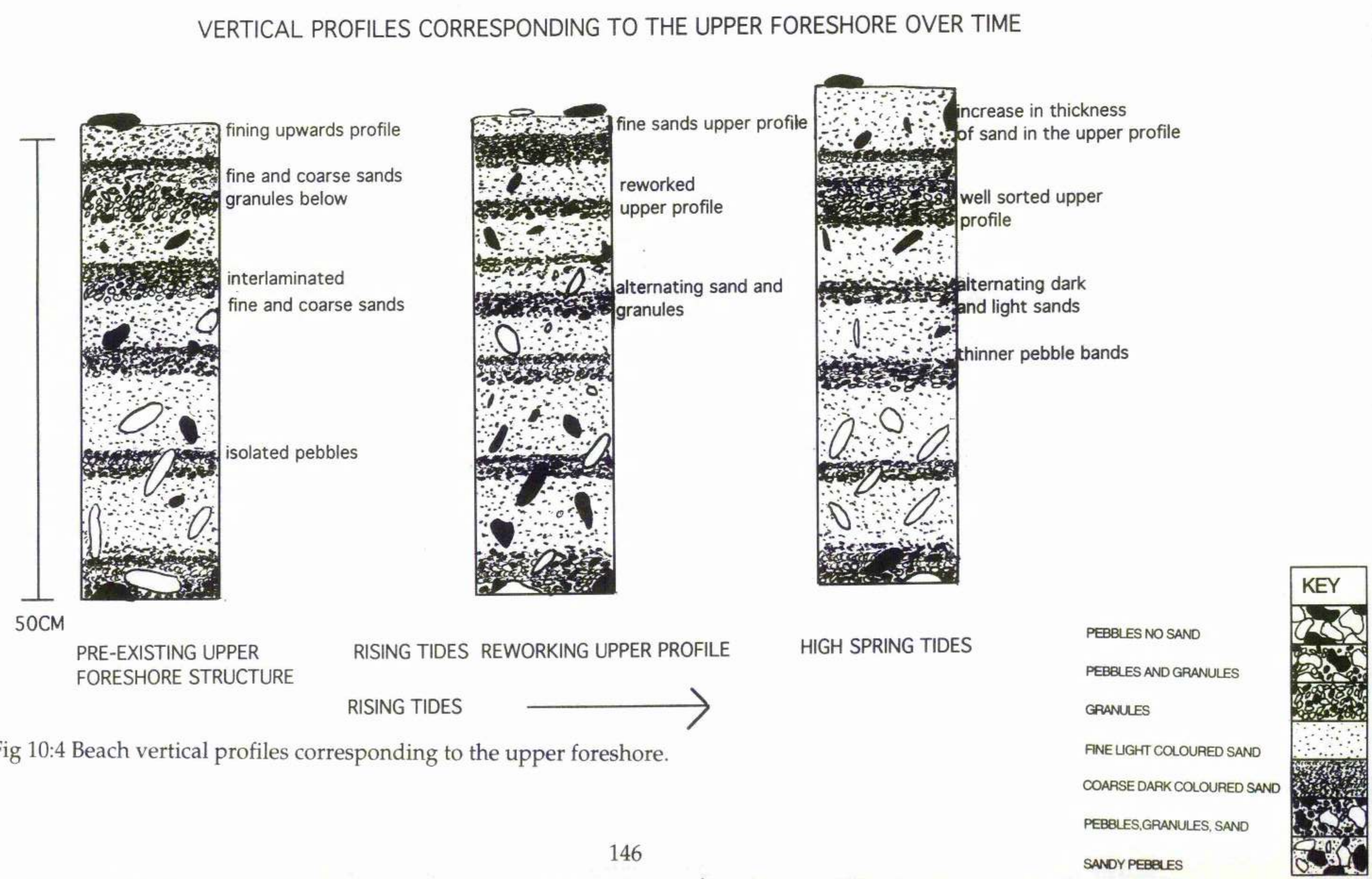


Fig 10:4 Beach vertical profiles corresponding to the upper foreshore.

VERTICAL PROFILES CORRESPONDING TO THE LOWER FORESHORE

There was difficulty inserting the freeze sampler when retrieving the vertical cores near the low water level. The vertical profiles lacked any particular structure, there was no segregation of the sand and pebbles into layers. The surface layers of the profile consisted of coarse dense equant and bladed pebbles, intermixed with fine pebbles and interstitial sand (figure 10:2). The poor sorting created a compact structure with a low permeability.

INTERPRETATION

The characteristics of the vertical profiles taken near low water on the mixed beach were attributed to the collision between the backwash which was carrying sediment and the next incoming swash which was also carrying sediment. At low water the vertical profiles were influenced by a powerful backwash. The gravity acceleration of the backwash was aided by the beach slope and was responsible for transporting coarse and fine pebbles towards the lower foreshore. The coarse pebbles were deposited at low water to create an immobile framework that trapped finer pebbles. In contrast, the sands were winnowed away or transported to lower depths in the beach profile by wave action. These processes accounted for the poorly sorted vertical structure of the lower foreshore profiles. The profiles corresponding to the lower foreshore did not change significantly over time.

10:13 DISCUSSION

The structure and composition of the vertical beach cores provided important insight into the sediment dynamics and the distribution of sand and pebbles on the mixed beach. With slight modification the freeze core sampler will provide a useful tool for investigating vertical beach profiles. The segregation of pebbles and sand into diagnostic layers with depth in the beach face could be traced alongshore. However, the thickness of the layers and the sediment size in the layers varied spatially and temporally. Therefore, it was assumed that the mobile layer of sediment undergoing longshore transport was not uniform. The lateral persistence of the layers in the vertical beach profiles broke down as the wave angle and height increased. Furthermore, cusps disrupted the longshore continuation of the layers. In addition, systematic changes in the vertical beach structure and composition were recorded at the cross shore positions. The mixed beach face was continually reworked by rising and falling tide levels and the vertical profiles were either modified or reassembled.

In conclusion, the distinct organisation of the vertical beach face was informative as to the mode of transport on the mixed beach. It is assumed that an upper more homogenous layer of coarse pebbles was transported over a less mobile layer of poorly sorted pebbles and sand. Consequently, the transport rate decreased rapidly with depth. In the following section, the importance of the vertical structure of the mixed beach is discussed in the light of beach stability.

11:1 DISCUSSION AND CONCLUDING REMARKS

The overall aim of the research was to investigate the transport of pebbles and sand on a mixed beach according to the wave and tidal climate. The results demonstrate that on the mixed beach the response of pebbles and sand in wave action differ markedly to the response of pebbles and sand reviewed in the literature on homogenous sand and shingle beaches. On the mixed beach the pebble composition, size, shape and sorting modified not only the rates of transport, but also the directions of transport. The research findings fully support the profound statement by Kirk (1980) who described mixed beaches as

" Morphologically distinct and dynamically complex"

The factors which influenced the response of pebbles and sand on the mixed beach are outlined below and assumptions are made as to the characteristics of the mobile layer of sediment undergoing longshore transport. Attention is then turned to an appraisal of the CERC formula on the mixed beach, with suggestions as to how the formula needs to be adapted to account for mixed beach sediment transport. Then finally, the sediment transport behaviour is examined in an assessment on the stability of the mixed beach.

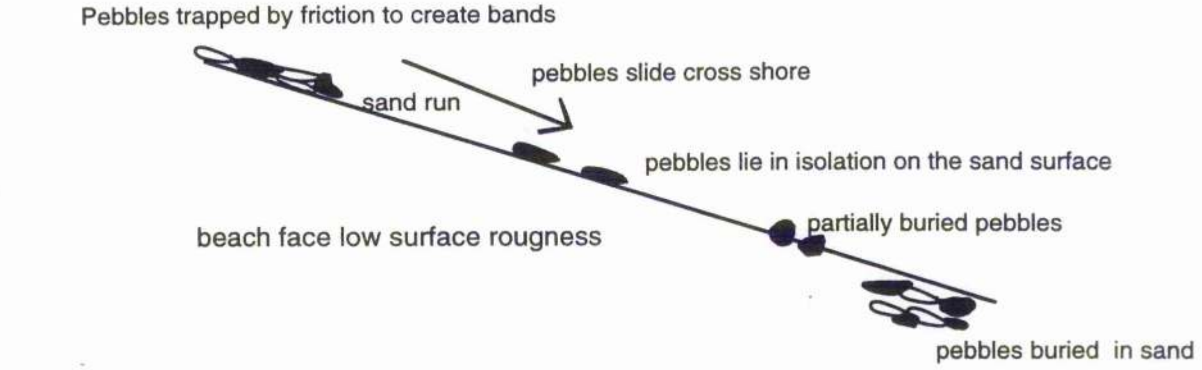
11:2 THE RESPONSE OF PEBBLE COMPOSITION AND SHAPE IN WAVE ACTION

Although, the coarse ironstone, sandstone and coal tracer pebbles were similar in size and shape, the pebbles responded differently in wave action. The crucial factor that influenced the hydraulic response of the pebbles in wave action was the specific gravity of the pebble, which was controlled by composition. The high density ironstone required a higher wave energy threshold to be reached before longshore transport took place, in contrast the sandstone pebbles were more readily entrained from the heterogeneous beach. Once in transport the composition of the pebble controlled the transport behaviour. The sandstone tracers were transported at a velocity 1.5 to 2 times the velocity of the ironstone tracer pebbles and as the wave power rose the transport rate of the sandstone tracer pebbles increased more rapidly in comparison to the ironstone pebbles. This was attributed to the 'wave selection' of the disc shaped sandstone pebbles, that were transported significantly further alongshore in suspension or by sliding over pebbles of other shapes. The high density of the ironstone pebbles restricted longshore transport. However, the transport in the backwash to the lower foreshore was enhanced. The unusual physical properties of the coal pebbles caused them to responded differently in wave action in comparison to the indigenous sandstone and ironstone pebbles. Observations revealed that the low density coal pebbles settled out of the water after the ironstone and sandstone had formed the framework of the beach. Consequently, the coal tracer pebbles lay unrestricted on the beach surface and were readily entrained, irrespective of the wave conditions. Once in transport, the coal pebbles were not incorporated into the moving bedload layer of rolling, saltating and sliding ironstone and sandstone pebbles. Thus, the coal pebbles were selectively transported by wave induced longshore currents, moving up to 200 metres in one tide, at velocities ten times that of the sandstone and ironstone pebbles. Furthermore, the rapid decline in the recovery rate and the substantial cross shore transport of the coal pebbles suggested that a high proportion of the coal pebbles were transported offshore in suspension. In the review of the literature, Carr (1971) Moss (1963) and Caldwell (1980) highlighted that pebbles of particular size and shape were selectively transported in wave action, however on this mixed beach there was also selective transport according to the pebble composition.

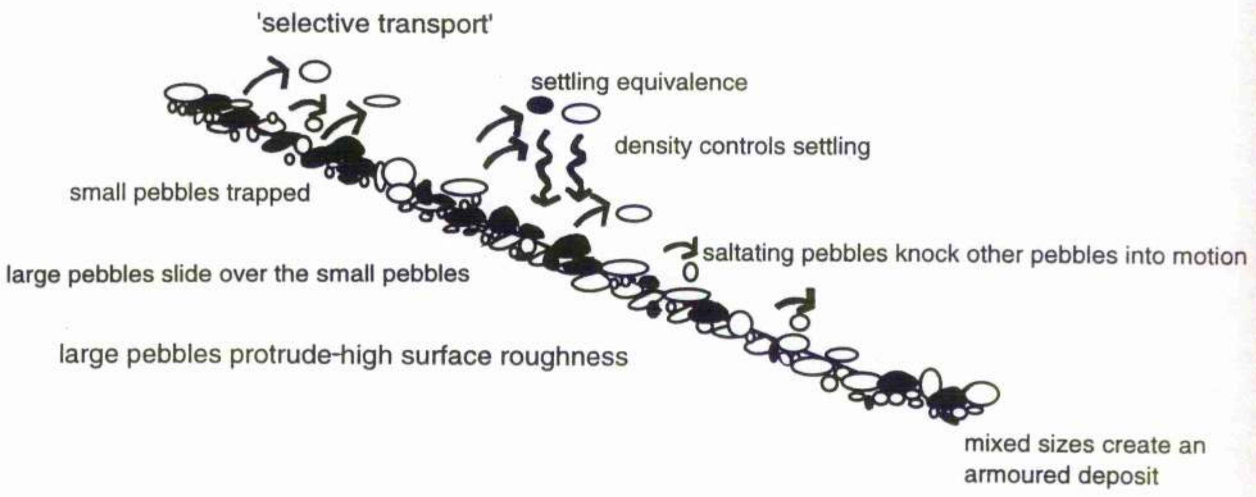
11:3 THE RESPONSE OF PEBBLE SIZE IN WAVE ACTION

In addition to pebbles of heterogeneous composition, the mixed beach had a wide spectrum of pebble sizes. Jolliffe (1964) identified that a particular size of wave moved a particular size of sediment. Carr (1971) and more recently Cooper et al (1996) similarly established a relationship between longshore transport and increasing pebble size. The differential transport of pebbles according to size was a particularly important phenomenon on the mixed beach due to the poor sorting of the beach sediments. In low wave energy conditions, the fine tracer pebbles and sand were selectively transported in preference to the coarse pebbles. Nevertheless, with an increase in the wave energy, these coarse pebbles were preferentially transported along the shore. The coarse pebbles protruded from the mixed beach face of closely packed smaller pebbles and generated turbulence in the boundary layer, that enhanced the lift forces responsible for initiating the transport of the coarse pebbles (figure 11:1). The critical shear stress for the entrainment of coarse pebbles from a mixed bed was therefore lower than on a beach face with uniform pebble sizes.

Once in transport the fine pebbles were trapped by the coarse pebbles and filtered deeper into the mixed beach framework so that, the longshore transport of the fine pebbles was reduced. This was supported by the inverse size grading observed in the vertical beach profiles that corresponded to the swash zone. The coarse pebbles had higher inertia and travelled further than the fine pebbles. The coarse pebbles were deposited after the fine pebbles had created the structure of the beach face and were more exposed to the oncoming swash than were the fine pebbles. Isla (1993) identified that on a mixed beach face, coarse round pebbles roll or ' overpass' a bed of finer pebbles and on deposition the coarse pebbles armoured the beach face. This mechanism of the overpassing of coarse pebbles over fine pebbles was evident on this mixed beach. In particular, the coarse dense ironstone pebbles armoured the beach face and trapped smaller pebbles beneath.



(a) Mixed beach with a high proportion of sand



(b) Mixed beach with a low proportion of sand

Fig 11:1 Mixed beach; the response of pebbles and sand

By combining the tracer results it is evident that the pebbles on the mixed beach did not behave as individuals. As the pebble form characteristics were heterogeneous, the entrainment and transport were strongly controlled by the composition and size of the neighbouring pebbles on the mixed beach. Imbalances of shear stresses were set up by the range of pebble sizes and compositions, consequently pulses of transport occurred as the various thresholds for transport were reached. The transport behaviour changed over time according to the sediment distribution, the vertical organisation of the mixed bed and the micro-topography of the beach, all of which were controlled by the wave and tidal climate. A range of transport opportunities were available, the pebbles were either incorporated into the beach framework or rejected and selectively transported alongshore. A similar analogy was made by Carter and Orford in (1991) to account for shingle barrier formation.

11:4 THE RESPONSE OF SAND ON THE MIXED BEACH

Although the literature is diverse on the response of sand and pebbles on homogenous sand and pebble beaches, the simultaneous transport of sand and pebbles has not been examined. On the mixed beach the sand and pebbles were transported in different directions and at different rates. The oscillatory wave swash action associated with the breaking waves directed wave energy landward and thus transported coarse pebbles alongshore. Whereas, the sands were simultaneously moved offshore in the backwash and then moved by longshore currents. The wave energy used to transport the sand, reduced the energy available for the longshore transport of the coarse pebbles.

A high proportion of sand on the mixed foreshore influenced the response of pebbles in wave action. Pebbles were either buried in the sand below the depth of disturbance or the sand partially buried the pebbles. Pebbles were also stranded in isolation on the sand surface of the mixed beach. As the pebbles do not experience imbrication and interlocking with other pebbles, it was first assumed that these pebbles would be more easily transported. However, when a high proportion of sand covered the mixed beach face the pebbles were less readily entrained, as the roughness coefficient and the shear stress available for pebble entrainment were lowered (figure 11:1). Once in motion, the mode of transport of the pebbles was influenced by the presence of sand. Sand cushioned the impacts of the saltating pebbles, in contrast to pebbles which knock one another into motion. Pebbles moved by rolling or sliding over the sand surface and they were trapped by the friction of the sand to create bands parallel to the shoreline. The backwash preferentially transported sand in between the pebbles to create sand runs in front of the pebble bands. The sand therefore enhanced the cross shore transport of the pebbles. This phenomenon supports the model produced by Nordstrom and Jackson (1993) (figure 9:11).

In conclusion, the pebble transport rates recorded on the mixed beach fluctuated as the wave energy and sediments interacted. In high wave energy the sand was moved offshore or trapped at depth leaving a more homogenous mobile layer of pebbles. The research findings compare to the work of Petrov (1989) who similarly identified the differential transport of heterogeneous pebbles and sand in wave action. The removal of sand from the mixed bed resulted in a mobile layer of more homogenous pebbles than the initial beach deposit. The fine sediments were transported alongshore or into the lower beach layer that was less mobile, whilst an upper layer of pebbles moved up and alongshore.

11:5 DEPTH OF DISTURBANCE ON THE MIXED BEACH

The depth of disturbance was monitored using vertical pebble and sand cores of known length. The cores recorded three possible outcomes; fresh deposition above an intact core, disturbance then deposition of a greater or lesser thickness or erosion of the core with no deposition. It was the wave parameters that determined the outcome recorded in the cores. Waves approaching normal to the shore were associated with an onshore transport with no significant longshore transport. With an increase in the wave angle the disturbance began to exceed the deposition of fresh sediment. As the wave height increased, the wave action combed down the foreshore and the disturbance exceeded deposition.

The literature reviewed on the depth of disturbance referred to pebble beaches on the South coast of England. Where the beaches are composed of homogenous coarse flint and chert pebbles that create a loose, open permeable beach framework, through which the swash and backwash can percolate. Therefore, the pebbles were mobile and the mean disturbance calculated by Bray (1993) was 12.5 cm in moderate wave conditions. In similar conditions, the disturbance recorded on this mixed beach was only 5 cm. As a result of the poor sorting and organisation of the vertical beach profiles the disturbance on the mixed beach had a value between a shingle beach and a sand beach. Consequently, the thickness of the mobile layer undergoing longshore transport is not as significant as on a homogeneous pebble beach.

When a high proportion of sand occurred on the mixed beach the sand was not in equilibrium with the steep mixed beach or the plunging waves. Consequently, the sand was readily transported offshore in one tide. In addition, the pebbles underlying the sand increased the permeability and the movement of water through the sand enhanced the disturbance of the beach face. In moderate wave conditions the mean disturbance on the mixed beach with a high proportion of sand was between 6 and 8 cm. In contrast, the literature on homogenous sand beaches referred to a mean disturbance of less than 5 cm (Komar 1970).

11:6 THE VERTICAL STRUCTURE OF THE MIXED BEACH

The freeze core sampler provided a useful tool for the investigation on the vertical structure of the mixed beach face. Although the mixed beach was a heterogeneous mix of coarse and fine pebbles and sand, the vertical beach structure was organised into characteristic layers with depth. The sediment layers could be traced cross shore and longshore, however the thickness and continuity of the layers were far from uniform. The structural organisation of the mixed beach was continually reworked and modified according to the prevailing tide and wave climate.

The vertical structure corresponding to the active swash zone of the mixed beach displayed inverse grading. The larger pebbles were deposited at the surface armouring the beach face. The coarse mobile pebbles at the surface were situated above a compacted layer of finer poorly sorted sediments, which experienced less movement. The transport rate therefore decreased rapidly with depth. On the lower foreshore the mobile sediment layer was thinner and the transport rate was reduced as the vertical profiles were poorly sorted and compact. Isla (1993) similarly identified gravel segregation at depth, as the wave action redistributed the mixed pebbles and sand to create a stable deposit, with the least probability of erosion.

It is possible that there is a change in the rate of transport as the beach structure develops and adjusts to the wave conditions. Early alteration of the structure will result in much transport and once there is stability in the structure it is probable that the transport rate will decrease.

In conclusion, the investigation revealed that the vertical beach structure played an important role in influencing the hydraulic characteristics of the swash and the subsequent longshore and cross shore transport. Furthermore, the beach structure provided insight into the sediment transport behaviour at depth in the mixed beach face. Beach armouring and the vertical segregation of the mixed beach face need to be studied in more detail as they provide important information with regard to the design of stable coastal defences. The reduced movement of the dense ironstone pebbles in comparison to the other pebble types, suggests that pebbles with high specific gravity might be significant in armouring and stabilising the beach face. Alternatively, it maybe the effect of the proportions of pebbles of different sizes and densities which can prevent offshore loss and reduce the thickness of the mobile layer of sediment undergoing longshore transport. Furthermore, the tracer experiment highlighted that is not possible to renourish a beach with foreign pebbles of different composition which are of low density or different size. The alien coal pebbles for example, were rejected from the indigenous beach sediment and potentially lost offshore.

11:7 APPRAISAL OF THE CERC SEDIMENT TRANSPORT FORMULA

The application of the CERC empirical formula related the pebble transport to the wave energy flux or wave power. The K value describes the efficiency of the wave power and its ability to move sediment. On the mixed beach there was no one universal coefficient value of K (figure 11:2). On the mixed beach the variation in the factor K was attributed to the size, sorting and composition of the pebbles. As these pebble form parameters varied spatially and temporally longshore, cross shore and at depth, it was evident that the empirical formula failed to incorporate the complexity of the mixed beach system.

Firstly, the longshore component of the wave energy flux which was used in the empirical quantification was far from uniform. The dominant Southeast waves were responsible for the net drift to the Southwest. However, locally generated wind waves that were variable in wave height and period were superimposed on the waves generated in the North sea. Consequently, there were differential rates of transport associated with periods of counterdrift. Refraction effects and the local bathymetry also played a significant role in influencing the rate of longshore transport at different positions along the shore. Furthermore, the cross shore transport associated with rising and falling tide levels was significant as the beach was narrow and the Firth controlled the tidal currents. However, the empirical formula did not distinguish the cross shore transport that was superimposed on the wave induced longshore transport.

Previously derived values of K for beaches along the South coast of England had values ranging between 0.021 and 0.041 (Bray 1990), similar K values were established at Hurst spit which ranged from 0.005 to 0.1 (Nicholls and Wright 1991). On this mixed beach whilst a relationship existed between the longshore component of wave energy and the rate of immersed pebble transport, the value of K varied considerably. It was pebble composition that was the crucial factor that effected the K coefficient (Table 11.1). Dense poorly sorted ironstone pebbles lowered the transport rate, whereas loose better sorted low density coal pebbles enhanced the transport rate. The unusual physical properties of the coal, in particular the low density, resulted in the coal pebbles responding similarly to sand in wave action. From the findings on the response of pebbles of different composition in wave action, it is proposed that on a heterogeneous pebble beach the density or settling velocity of the pebbles would be a more useful and suitable parameter for predicting the transport rate.

COMPOSITION	K COEFFICIENT RANGE	MEAN K COEFFICIENT
IRONSTONE	0.023-0.0011	0.0058
SANDSTONE	0.048-0.002	0.010
COAL	0.2-0.004	0.039

TABLE 11.1 K coefficient values.

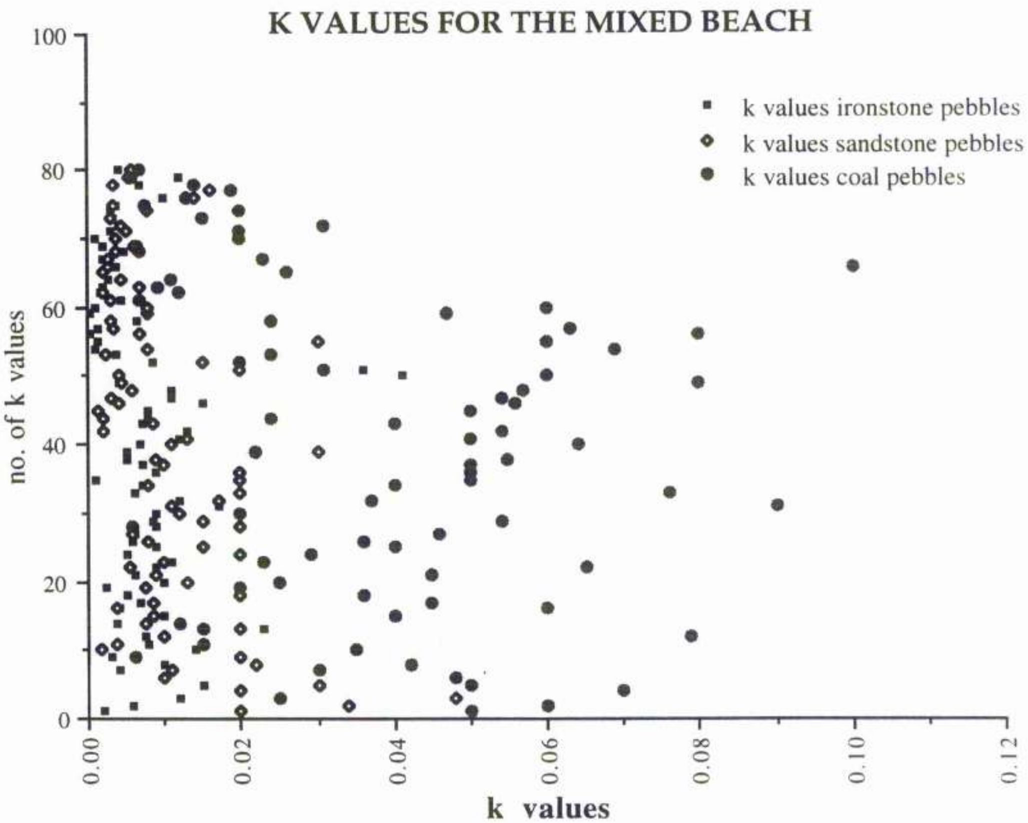


Fig 11:2 The range of K values for the mixed beach.

The conclusions drawn from the comparison of the fine and coarse pebble tracers also had significant implications of the quantification of the transport rate on the mixed beach. The CERC formula assumed that the size distribution on the beach was uniform, which was far from the situation found on the mixed beach, which was poorly sorted throughout. Transport rates derived solely from the transport of the coarse tracer pebbles overestimate the transport rate on the mixed beach. For a more precise quantification of the sediment transport on the mixed beach, the formula calibration needs to take into account the proportions of the pebble sizes present. Furthermore, the sand and pebbles on the mixed beach often moved in different transport directions and at different rates. Consequently, the coefficient K required separate quantification. The proportion of sand on the mixed beach caused the pebble transport rate to fluctuate, which accounted for some of the variation in the K values. An overestimation of the value K occurred when a high proportion of sand was present on the foreshore.

On the mixed beach the poor sorting and compaction of the beach face, effected the permeability and consequently the mobility of the pebbles. The empirical formula includes a standard approximation of the void ratio or porosity which is 0.6, however on the mixed beach the porosity was significantly lower. To increase the efficiency of the calibration a better approximation of the void ratio for mixed beaches is required.

As the transport on the mixed beach was sensitive to the characteristics of the bed material and bed roughness the formula of Bijker (1971) would be more appropriate than the CERC formula. Furthermore, the Bijker formula assumes that there is a substantial difference in the mode of transport of the coarse and fine grains.

$$Sb = 5D50\frac{v}{C}g\frac{1}{2}\exp\left[\frac{-0.27\Delta \mathrm{D50}\rho \mathrm{g}}{\mu\tau\left[1+\frac{1}{2}\left(\frac{uo}{v}\right)2\right]}\right] \qquad \text{(equation 11:1)}$$

Where Sb= bedload(m3/sm) including pores; D50 particle diameter; V Mean current velocity; C chezy coefficient; g gravitational acceleration; Δ relative apparent density of the bed material.

There is still a long way to go before sediment transport on mixed beaches is calibrated. The prediction of transport rates on the mixed beach with pebbles and sand requires a highly modified formula, that incorporates several interdependent sediment and wave parameters.

As the empirical equation overlooked many fundamental observations, the qualitative assessment was very informative of the actual transport behaviour of the pebbles. Future tracer surveys need to model the spectrum of pebble sizes, shapes and compositions and the recording of continuos paths followed by the tracers will also be highly informative. Furthermore, the taking of vertical cores will enable an assessment to be made of the form of the mobile layer and the likely transport rates at depth below the beach face. The role of beach armouring as a method of maintaining beach stability and renourishment should also be addressed.

11:8 STABILITY ASSESSMENT EAST WEMYSS

The tracer information in conjunction with the monitoring of the disturbance of the beach, indicates an offshore loss of sediment is occurring. Below the veneer of the loose coarse pebbles, there is a compact impermeable core of material. The ironstone pebbles create a coarse lag deposit that forms a steep foreshore. The erosion along this coastline is undoubtedly related to the reduction in supply of fresh beach material from the colliery bings. It is apparent from the unusual physical properties of the coal that there is no site to the Southwest which is gaining the coal material. Offshore loss will continue even if longshore losses are prevented. The offshore loss of sediments and scour is exposing fresh rock platforms (plate 11:1). Ultimately, once all of the colliery waste has been removed from the protective cliff foot terraces fronting East Wemyss, wave attack will be directed at the cliffs themselves.

It is beyond the scope of this research to predict where the coal waste has gone however assumptions can be made based on the behaviour of the coal. Due to the density difference and the hydraulic properties of the coal there must be a high concentration offshore. An assessment of hydrodynamic flow patterns, in particular residual flow eddies in conjunction with the bathymetry, will distinguish favourable pathways for suitable coal deposits in sinks. In addition, a seismic survey of the acoustic impedance from different seabed materials would recall the character of the sediments at the bed. It may even be that offshore mining would be an effective way of recycling the waste if significant deposits are located.

Already the effect of changes in the sediment supply are being witnessed. Much of the development close to the shoreline since mining began will be at risk from the erosion. Reclaimed land built out into the sea during the mining era forms the frontage of East Wemyss village and is particularly susceptible to attack from the sea (plate 11:2). Temporary rock armouring has been placed along this section. However service pipes, an amenity area and car park are all under threat, as erosion either side of the temporary strong point is accelerating (plate 11:3). Many houses predate the use of waste dumping and are founded on solid rock, nevertheless, removal of the waste platform by erosion will make access more difficult and poses a flood risk.

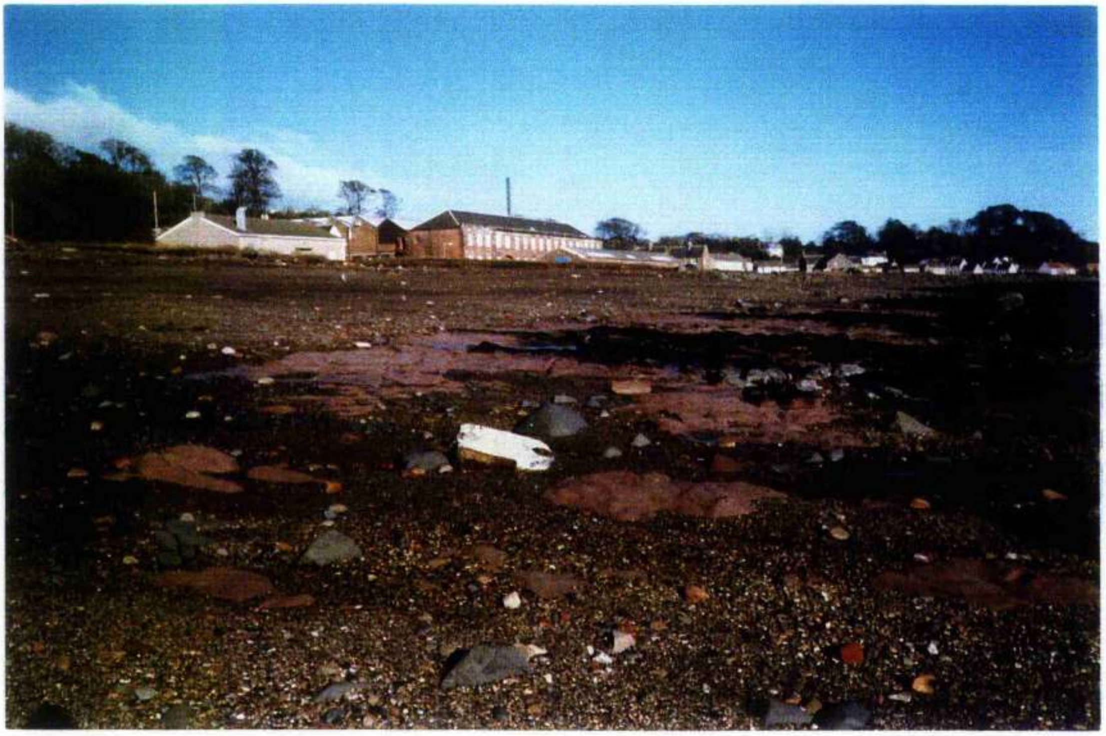


Plate 11:1 Exposure of the rock cut platform.

Plate 11:2 Erosion along the frontage of East Wemyss.

Plate 11:3 Rock Armouring.

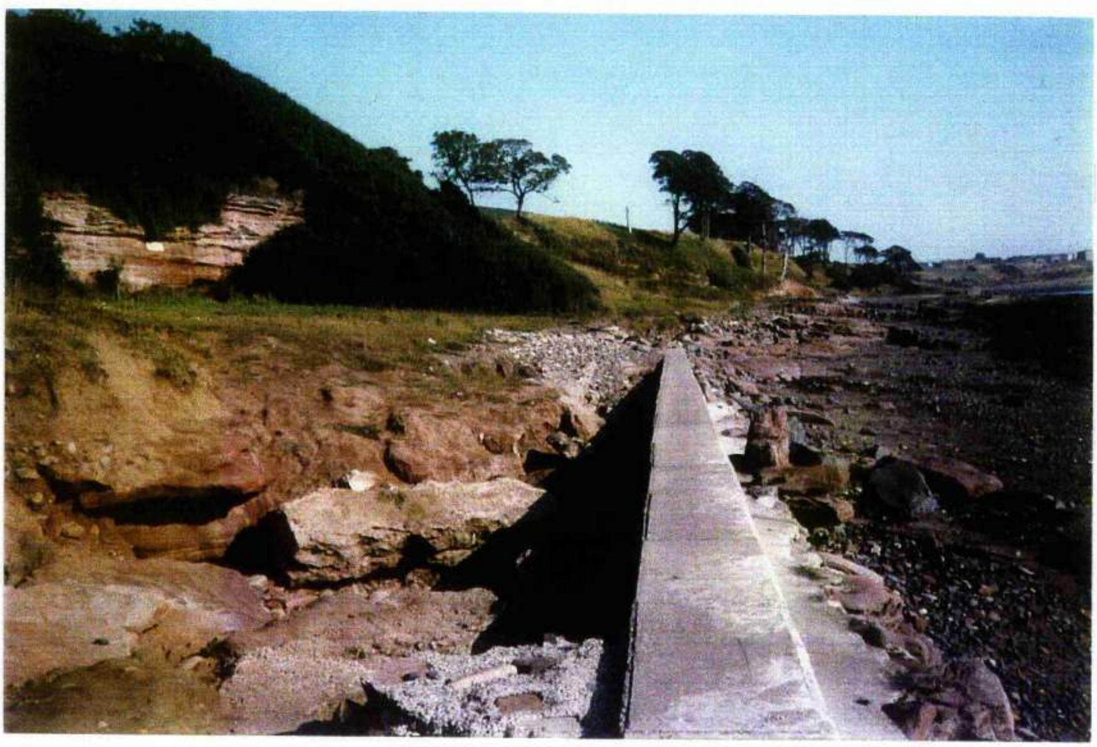


Plate 11:4 Erosion of the access path to the Wemyss Caves.

There is particular concern over the archaeological site of the Wemyss caves, that contain more authenticated cave markings than elsewhere in Britain and draw visitors from all over the world. The caves have a long history of inhabitancy which stems back to the Bronze Age, Pictish (pre-Christian Iron Age), Christian and Viking eras. Previously, a Public Right of Way extended along the coastline from West Wemyss to Buckhaven providing access to the caves, however with the retreat of the coastline this pathway has been destroyed (plate 11:4). The weak sandstone of the caves is particularly susceptible to erosion and collapse as a result of mining subsidence has already resulted in the closure of several caves and others are held up by wooden or brick supports.

Since the effects of coastal erosion in the East Wemyss area became evident many small scale and short term attempts have been made to correct the problems at local 'hot spots', by tipping rubble, building ashlar or concrete walls or more recently by constructing 'cribbing' systems to provide isolated strong points (plate 11:5). Individually these have limited effect as subsidence has caused beach lowering which undermines the protection works. Any attempts to restrict the longshore transport of the sediments by groynes and breakwaters will not prevent erosion, as the unique behaviour of the coal causes offshore loss. HR Wallingford (1994) predicted that in 10 years the coastline will revert to the 1895 pre-mining position. However, as a result of the local rise in sea level due to mining subsidence and the reduction in the supply of sediment, the coastline will be subject to further erosion beyond the pre-mining coastline, therefore the issue of the changes along the entire coast from Methil to Kirkcaldy needs to be addressed with some urgency.

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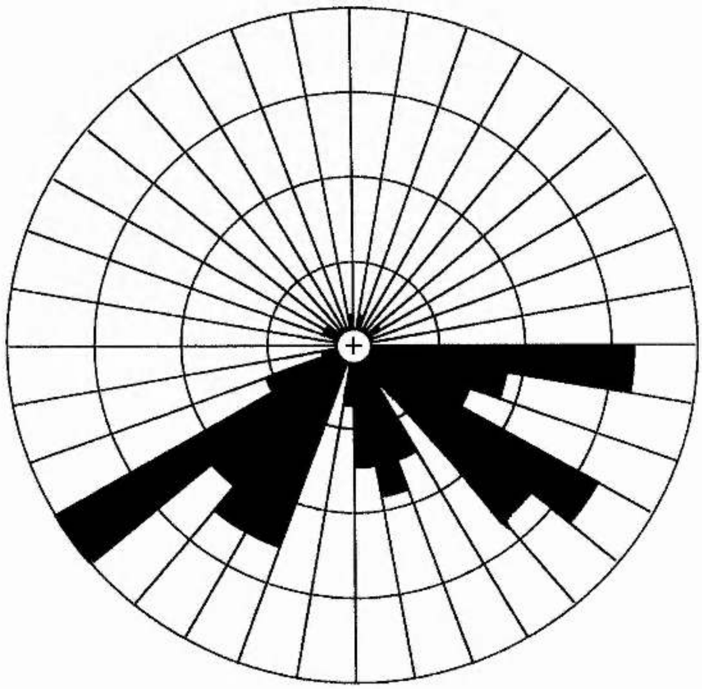

Appendix Figure 6:A Wave Rose Data Pebble tracer Survey.

EXPERIMENT 1	TIDE MEAN (M)	US (M/S)	DISTURBANCE	Q (M/S3)	Il (M/S3)	K VALUE	WAVE POWER
1-Apr							
MAX COAL	14.100	0.00098	0.044	0.00043	2.470	0.015	166.700
S/S	1.000	0.00007		0.00003	0.300	0.002	
I/S	0.000						
MEAN COAL	5.300	0.00036		0.00016	0.920	0.006	
S/S	0.600	0.00004		0.00002	0.200	0.001	
I/S	0.000						
2-Apr							
MAX COAL	12.530	0.00087	0.025	0.00026	1.500	0.015	102.550
S/S	1.950	0.00014		0.00004	0.400	0.004	
I/S	0.000						
MEAN COAL	5.040	0.00035		0.00011	0.630	0.006	
S/S	0.250	0.00017		0.00005	0.480	0.005	
I/S	0.000						
3-Apr							
MAX COAL	21.000	0.00150	0.039	0.00088	5.040	0.023	223.900
S/S	3.100	0.00022		0.00013	1.200	0.006	
I/S	1.950	0.00010		0.00006	0.650	0.003	
MEAN COAL	6.600	0.00046		0.00027	1.550	0.007	
S/S	0.820	0.00006		0.00003	0.320	0.001	
I/S	0.230	0.00002		0.00001	0.104	0.000	
4-Apr							
MAX COAL	18.210	0.00130	0.038	0.00074	4.200	0.040	106.400
S/S	2.710	0.00019		0.00011	1.050	0.010	
I/S	0.750	0.00005		0.00003	0.320	0.000	
MEAN COAL	5.200	0.00036		0.00021	1.200	0.011	
S/S	0.500	0.00004		0.00002	0.200	0.002	
I/S	0.300	0.00002		0.00001	0.130	0.001	
5-Apr							
MAX COAL	37.590	0.00260	0.048	0.00019	10.900	0.040	263.970
S/S	5.650	0.00039		0.00028	2.700	0.010	
I/S	1.150	0.00008		0.00006	0.630	0.002	
MEAN COAL	12.010	0.00083		0.00059	3.400	0.013	
S/S	1.640	0.00011		0.00008	0.750	0.003	
I/S	0.500	0.00006		0.00004	0.440	0.002	
6-Apr							
MAX COAL	60.400	0.00420	0.061	0.00380	21.800	0.050	460.000
S/S	12.300	0.00085		0.00078	7.500	0.020	
I/S	8.400	0.00060		0.00050	5.800	0.012	
MEAN COAL	18.460	0.00130		0.00120	6.900	0.015	
S/S	3.900	0.00027		0.00025	2.400	0.005	
I/S	1.980	0.00013		0.00012	1.300	0.003	
7-Apr							
MAX COAL	68.200	0.00470	0.058	0.00410	24.000	0.050	465.400
S/S	8.540	0.00059		0.00051	4.900	0.010	
I/S	4.350	0.00030		0.00026	2.900	0.006	
MEAN COAL	14.900	0.00100		0.00009	5.200	0.010	
S/S	3.610	0.00025		0.00022	2.100	0.005	
I/S	1.500	0.00030		0.00009	0.990	0.002	
8-Apr							53.170
MAX COAL	13.810	0.00096	0.043	0.00062	3.500	0.060	
S/S	4.500	0.00031		0.00019	1.800	0.034	
I/S	2.200	0.00015		0.00010	0.990	0.002	
MEAN COAL	3.700	0.00026		0.00017	1.100	0.020	
S/S	1.300	0.00009		0.00006	1.600	0.030	
I/S	0.800	0.00006		0.00004	0.400	0.008	
9-Apr							
MAX COAL	21.100	0.00150	0.055	0.00120	6.900	0.045	
S/S	6.050	0.00042		0.00035	3.300	0.020	154.100
I/S	3.300	0.00023		0.00019	2.100	0.014	

MEAN COAL	6.200	0.00043		0.00035	2.010	0.013	
S/S	2.040	0.00014		0.00012	1.200	0.008	
I/S	1.500	0.00010		0.00009	0.900	0.007	
10-Apr							
MAX COAL	25.100	0.00140	0.047	0.00099	5.680	0.070	81.990
S/S	10.500	0.00058		0.00041	3.920	0.048	
I/S	2.700	0.00015		0.00011	1.200	0.015	
MEAN COAL	5.900	0.00033		0.00022	1.300	0.015	
S/S	1.760	0.00010		0.00007	0.660	0.008	
I/S	0.710	0.00004		0.00003	0.300	0.004	
11-Apr							
MAX COAL	8.050	0.00560	0.051	0.00043	2.460	0.016	153.300
S/S	2.290	0.00016		0.00012	1.170	0.008	
I/S	2.100	0.00015		0.00011	1.270	0.008	
MEAN COAL	2.130	0.00015		0.00011	0.630	0.004	
S/S	0.980	0.00007		0.00005	0.500	0.003	
I/S	0.630	0.00004		0.00005	0.400	0.002	
12-Apr							
MAX COAL	94.800	0.00660	0.078	0.00620	35.500	0.056	
S/S	10.970	0.00076		0.00071	6.800	0.011	
I/S	6.300	0.00044		0.00041	4.500	0.007	629.900
MEAN COAL	25.900	0.00180		0.00170	9.700	0.015	
S/S	3.720	0.00026		0.00024	2.300	0.004	
I/S	2.900	0.00020		0.00019	2.100	0.003	
13-Apr							
MAX COAL	174.100	0.01200	0.088	0.00160	90.800	0.047	1937.300
S/S	30.300	0.00210		0.00280	26.500	0.014	
I/S	18.900	0.00130		0.00170	18.900	0.010	
MEAN COAL	37.390	0.00260		0.00340	19.500	0.010	
S/S	7.900	0.00054		0.00071	6.800	0.004	
I/S	4.500	0.00031		0.00040	4.500	0.002	
EXPERIMENT 2 14/5							155.400
MAX COAL	35.600	0.00250	0.038	0.00094	5.400	0.035	
S/S	5.300	0.00037		0.00014	1.340	0.009	
I/S	4.100	0.00028		0.00011	1.200	0.008	
MEAN COAL	11.600	0.00081		0.00031	1.720	0.011	
S/S	2.520	0.00018		0.00007	0.640	0.004	
I/S	1.580	0.00011		0.00004	0.460	0.003	
15-May							
MAX COAL	17.003	0.00120	0.034	0.00041	2.340	0.050	45.600
S/S	2.060	0.00014		0.00005	0.460	0.010	
I/S	1.000	0.00007		0.00002	0.300	0.006	
MEAN COAL	3.120	0.00022		0.00007	0.400	0.009	
S/S	0.570	0.00004		0.00001	0.113	0.003	
I/S	0.340	0.00002		0.00001	0.089	0.002	
16-May							
MAX COAL	20.900	0.00150	0.059	0.00130	7.600	0.020	396.600
S/S	7.900	0.00055		0.00049	4.700	0.012	
I/S	3.800	0.00026		0.00023	2.540	0.006	
MEAN COAL	8.300	0.00058		0.00051	2.900	0.007	
S/S	1.800	0.00013		0.00011	1.060	0.003	
I/S	0.500	0.00004		0.00003	0.340	0.001	
17-May							
MAX COAL	78.200	0.00540	0.051	0.00410	23.700	0.055	427.990
S/S	11.600	0.00081		0.00062	5.890	0.014	
I/S	5.280	0.00037		0.00028	3.100	0.007	
MEAN COAL	20.670	0.00140		0.00110	6.300	0.015	
S/S	3.580	0.00025		0.00019	1.820	0.004	
I/S	1.260	0.00009		0.00007	0.740	0.002	
18-May							
MAX COAL	110.360	0.00770	0.081	0.00750	42.900	0.054	

S/S	13.200	0.00092		0.00089	8.500	0.011	790.000
I/S	8.500	0.00059		0.00057	6.300	0.008	
MEAN COAL	43.050	0.00029		0.00290	16.600	0.020	
S/S	4.200	0.00029		0.00028	2.710	0.003	
I/S	3.250	0.00026		0.00022	2.400	0.003	
19-May							
MAX COAL	7.300	0.00050	0.051	0.00040	2.220	0.025	
S/S	5.200	0.00040		0.00003	2.600	0.030	90.800
I/S	1.800	0.00013		0.00099	1.090	0.012	
MEAN COAL	3.700	0.00026		0.00019	1.130	0.012	
S/S	0.940	0.00007		0.00005	0.500	0.005	
I/S	0.220	0.00002		0.00001	0.130	0.001	
20-May							
MAX COAL	0.000		0.098				
S/S	31.000	0.00210		0.00380	36.300	0.016	2321.000
I/S	20.600	0.00140		0.00250	27.800	0.012	
MEAN COAL	0.000						
S/S	11.500	0.00079		0.00140	13.400	0.006	
I/S	6.900	0.00048		0.00084	9.300	0.004	
21-May							415.700
MAX COAL	26.300	0.00180	0.073	0.00160	9.200	0.022	
S/S	9.200	0.00064		0.00056	5.300	0.013	
I/S	6.400	0.00044		0.00039	4.300	0.010	
MEAN COAL	8.340	0.00058		0.00051	2.900	0.007	
S/S	3.900	0.00028		0.00024	2.300	0.006	
I/S	2.610	0.00016		0.00014	1.500	0.004	
22-May							
MAX COAL	57.100	0.00390	0.049	0.00290	16.700	0.058	
S/S	11.100	0.00077		0.00057	5.400	0.020	289.700
I/S	5.100	0.00035		0.00026	2.870	0.010	
MEAN COAL	21.090	0.00150		0.00110	6.200	0.020	
S/S	3.300	0.00023		0.00017	1.610	0.006	
I/S	0.960	0.00007		0.00005	0.500	0.002	
EXPERIMENT 3 24/6							
MAX COAL	18.200	0.00130	0.038	0.00049	2.860	0.048	
S/S	3.900	0.00027		0.00010	0.980	0.020	59.300
I/S	2.100	0.00015		0.00006	0.600	0.010	
MEAN COAL	4.600	0.00032		0.00012	0.700	0.012	
S/S	0.580	0.00004		0.00002	0.150	0.003	
I/S	0.390	0.00003		0.00001	0.110	0.002	
25-Jun							
MAX COAL	111.100	0.00770	0.059	0.00450	26.100	0.050	
S/S	33.000	0.00230		0.00140	12.900	0.030	489.700
I/S	10.100	0.00069		0.00041	4.500	0.009	
MEAN COAL	40.650	0.00280		0.00170	9.500	0.020	
S/S	3.840	0.00027		0.00016	1.500	0.003	
I/S	2.160	0.00015		0.00009	0.970	0.002	
26-Jun							
MAX COAL	156.400	0.01100	0.049	0.00640	36.600	0.100	
S/S	11.000	0.00076		0.00045	4.300	0.011	396.500
I/S	8.120	0.00056		0.00033	3.650	0.009	
MEAN COAL	54.300	0.00380		0.00220	12.700	0.032	
S/S	4.840	0.00034		0.00019	1.890	0.005	
I/S	1.950	0.00014		0.00008	0.870	0.002	
27-Jun							
MAX COAL	51.000	0.00350	0.052	0.00220	12.600	0.037	341.000
S/S	14.200	0.00099		0.00062	5.900	0.017	
I/S	6.100	0.00042		0.00003	2.900	0.009	
MEAN COAL	13.140	0.00093		0.00058	3.300	0.010	
S/S	2.950	0.00020		0.00013	1.200	0.004	
I/S	0.750	0.00012		0.00008	0.840	0.003	

28-Jun							
MAX COAL	65.100	0.00420	0.045	0.00240	13.990	0.054	
S/S	6.050	0.00042		0.00023	2.170	0.008	258.400
I/S	3.900	0.00027		0.00015	1.600	0.006	
MEAN COAL	20.080	0.00140		0.00075	4.300	0.020	
S/S	1.670	0.00012		0.00006	0.600	0.002	
I/S	0.500	0.00003		0.00002	0.200	0.001	
29-Jun							
MAX COAL	61.000	0.00400	0.048	0.00300	17.500	0.600	269.500
S/S	8.200	0.00060		0.00040	3.900	0.015	
I/S	4.600	0.00032		0.00023	2.500	0.009	
MEAN COAL	17.690	0.00120		0.00089	5.100	0.019	
S/S	3.960	0.00027		0.00019	1.900	0.007	
I/S	0.880	0.00006		0.00004	0.500	0.002	
30-Jun							
MAX COAL	100.000	0.00690	0.039	0.00400	23.000	0.100	322.000
S/S	16.500	0.00110		0.00065	6.200	0.020	
I/S	7.600	0.00005		0.00031	3.400	0.011	
MEAN COAL	31.690	0.00220		0.00130	7.400	0.023	
S/S	3.950	0.00027		0.00016	1.500	0.005	
I/S	1.910	0.00013		0.00008	0.850	0.003	
EXPERIMENT 3 1/7							
MAX COAL	31.000	0.00220	0.044	0.00140	8.100	0.029	
S/S	3.800	0.00026		0.00017	1.700	0.006	284.000
I/S	2.900	0.00020		0.00013	1.500	0.005	
MEAN COAL	11.180	0.00078		0.00050	2.940	0.010	
S/S	1.840	0.00013		0.00008	0.811	0.003	
I/S	0.950	0.00007		0.00004	0.500	0.002	
2-Jul							
MAX COAL	54.000	0.00400	0.038	0.00170	9.800	0.046	212.000
S/S	10.300	0.00072		0.00033	3.120	0.015	
I/S	3.500	0.00024		0.00011	1.220	0.006	
MEAN COAL	16.470	0.00110		0.00052	2.990	0.014	
S/S	1.900	0.00013		0.00006	0.570	0.003	
I/S	0.900	0.00006		0.00003	0.300	0.002	
3-Jul							
MAX COAL	10.000	0.00069	0.026	0.00027	1.600	0.050	33.400
S/S	2.900	0.00020		0.00008	0.800	0.023	
I/S	0.000	0.00000		0.00000	0.000		
MEAN COAL	3.910	0.00027		0.00011	0.610	0.018	
S/S	0.840	0.00006		0.00002	0.220	0.007	
I/S	0.000	0.00000		0.00000			
4-Jul							
MAX COAL	76.000	0.00530	0.067	0.00530	30.400	0.054	561.000
S/S	7.000	0.00048		0.00049	4.670	0.008	
I/S	3.800	0.00026		0.00026	2.900	0.005	
MEAN COAL	25.780	0.00180		0.00180	10.300	0.020	
S/S	3.390	0.00024		0.00024	2.300	0.004	
I/S	1.070	0.00007		0.00008	0.800	0.002	
5-Jul							
MAX COAL	150.000	0.01000	0.079	0.00990	56.600	0.057	990.500
S/S	20.200	0.00140		0.00130	12.700	0.012	
I/S	10.600	0.00074		0.00069	7.700	0.008	
MEAN COAL	31.800	0.00220		0.00210	12.000	0.012	
S/S	4.420	0.00031		0.00029	2.800	0.003	
I/S	1.060	0.00011		0.00011	1.200	0.001	
6-Jul							
MAX COAL	29.100	0.00200	0.046	0.00170	9.750	0.079	123.300
S/S	8.200	0.00057		0.00047	4.500	0.037	
I/S	4.400	0.00031		0.00025	2.800	0.023	
MEAN COAL	9.570	0.00066		0.00055	3.200	0.026	

S/S	1.710	0.00012		0.00010	0.900	0.008	
I/S	0.820	0.00006		0.00005	0.520	0.004	
7-Jul							
MAX COAL	21.300	0.00150	0.031	0.00056	3.200	0.042	
S/S	3.400	0.00024		0.00009	0.840	0.011	
I/S	2.800	0.00019		0.00007	0.800	0.010	76.700
MEAN COAL	3.690	0.00026		0.00010	0.550	0.007	
S/S	1.050	0.00007		0.00000	0.300	0.003	
I/S	0.520	0.00036		0.00001	0.150	0.002	
8-Jul							
MAX COAL	28.300	0.00196	0.052	0.00150	8.800	0.037	
S/S	9.300	0.00065		0.00050	4.800	0.020	247.300
I/S	3.900	0.00027		0.00021	2.300	0.009	
MEAN COAL	10.670	0.00074		0.00058	3.300	0.013	
S/S	0.950	0.00007		0.00005	0.500	0.002	
I/S	0.390	0.00003		0.00002	0.230	0.001	
9-Jul							
MAX COAL	13.000	0.00090	0.028	0.00030	1.700	0.012	142.000
S/S	5.000	0.00038		0.00013	1.230	0.009	
I/S	2.000	0.00014		0.00005	0.500	0.004	
MEAN COAL	4.910	0.00034		0.00011	0.700	0.005	
S/S	1.850	0.00013		0.00004	0.400	0.003	
I/S	0.580	0.00004		0.00001	0.140	0.001	
10-Jul							
MAX COAL	42.500	0.00290	0.076	0.00230	12.900	0.024	542.300
S/S	12.950	0.00089		0.00068	6.500	0.012	
I/S	4.300	0.00029		0.00023	2.500	0.005	
MEAN COAL	11.720	0.00081		0.00062	3.500	0.007	
S/S	2.080	0.00014		0.00011	1.050	0.002	
I/S	1.000	0.00007		0.00005	0.600	0.001	
EXPERIMENT 4 12/8							
MAX COAL	106.100	0.00740	0.089	0.01200	68.000	0.060	1145.000
S/S	18.000	0.00130		0.00200	19.000	0.020	
I/S	10.500	0.00073		0.00120	12.900	0.011	
MEAN COAL	41.700	0.00290		0.00460	27.000	0.020	
S/S	5.080	0.00035		0.00056	5.300	0.005	
I/S	3.850	0.00026		0.00042	4.700	0.004	
13-Aug							
MAX COAL	125.600	0.00870	0.083	0.01300	74.700	0.060	1195.800
S/S	15.300	0.00110		0.00160	10.200	0.009	
I/S	7.200	0.00050		0.00075	8.200	0.007	
MEAN COAL	45.700	0.00320		0.00470	27.200	0.023	
S/S	6.900	0.00048		0.00072	6.800	0.006	
I/S	3.440	0.00024		0.00036	3.900	0.003	
14-Aug							
MAX COAL	43.100	0.00290	0.071	0.00380	22.000	0.040	585.000
S/S	6.300	0.00044		0.00056	5.300	0.009	
I/S	4.200	0.00029		0.00037	4.100	0.007	
MEAN COAL	18.200	0.00130		0.00170	9.300	0.020	
S/S	2.720	0.00019		0.00240	2.300	0.004	
I/S	1.930	0.00013		0.00017	1.900	0.003	
15-Aug							
MAX COAL	25.100	0.00200	0.048	0.00150	8.600	0.060	144.600
S/S	5.800	0.00040		0.00035	3.300	0.020	
I/S	2.400	0.00017		0.00014	1.600	0.010	
MEAN COAL	10.300	0.00070		0.00060	3.400	0.024	
S/S	2.030	0.00014		0.00012	1.200	0.008	
I/S	0.530	0.00004		0.00003	0.400	0.002	
16-Aug							
MAX COAL	5.600	0.00039	0.026	0.00018	1.040	0.030	38.900
S/S	2.800	0.00019		0.00009	0.900	0.022	

I/S							
MEAN COAL	0.980	0.00007		0.00003	0.200	0.002	
S/S	0.850	0.00006		0.00003	0.300	0.007	
I/S							
18-Aug							
MAX COAL	31.100	0.00220	0.033	0.00011	6.100	0.036	171.800
S/S	3.900	0.00030		0.00013	1.300	0.008	
I/S	1.900	0.00013		0.00006	0.600	0.004	
MEAN COAL	8.900	0.00060		0.00025	1.400	0.008	
S/S	1.260	0.00009		0.00004	0.400	0.002	
I/S	0.310	0.00002		0.00001	0.120	0.001	
20-Aug							
MAX COAL	15.000	0.00100	0.028	0.00050	3.000	0.060	
S/S	3.500	0.00024		0.00012	1.200	0.020	58.000
I/S	0.500	0.00038		0.00002	0.200	0.004	
MEAN COAL	2.790	0.00019		0.00010	0.600	0.012	
S/S	0.730	0.00005		0.00003	0.240	0.005	
I/S	0.250	0.00002		0.00000	0.090	0.011	
21-Aug							
MAX COAL	72.300	0.00500	0.068	0.00600	35.000	0.070	
S/S	18.200	0.00130		0.00150	15.000	0.030	515.000
I/S	7.400	0.00050		0.00063	6.900	0.013	
MEAN COAL	32.290	0.00220		0.00270	16.000	0.031	
S/S	5.030	0.00035		0.00043	4.100	0.008	
I/S	1.820	0.00013		0.00015	1.710	0.003	
22-Aug							
MAX COAL	69.100	0.04800	0.064	0.00550	31.600	0.065	
S/S	7.100	0.00049		0.00057	5.400	0.011	497.900
I/S	4.100	0.00028		0.00033	3.600	0.007	
MEAN COAL	39.650	0.00280		0.00032	18.200	0.040	
S/S	4.000	0.00026		0.00032	3.100	0.006	
I/S	2.870	0.00020		0.00023	2.500	0.005	
23-Aug							
MAX COAL	75.400	0.00520	0.065	0.00510	29.000	0.050	595.000
S/S	16.000	0.00110		0.00110	10.400	0.020	
I/S	10.500	0.00072		0.00071	7.800	0.013	
MEAN COAL	25.500	0.00180		0.00180	10.200	0.017	
S/S	6.270	0.00040		0.00042	4.100	0.007	
I/S	3.270	0.00030		0.00022	2.440	0.004	
EXPERIMENT 5 1/9							
MAX COAL	13.200	0.00072	0.041	0.00068	3.500	0.020	171.000
S/S	5.100	0.00028		0.00023	2.200	0.013	
I/S	1.900	0.00013		0.00011	1.200	0.007	
MEAN COAL	4.200	0.00029		0.00020	1.100	0.006	
S/S	0.830	0.00005		0.00004	0.400	0.002	
I/S	0.590	0.00003		0.00003	0.300	0.002	
2-Sep							
MAX COAL	9.000	0.00630	0.038	0.00047	2.700	0.025	
S/S	1.900	0.00130		0.00010	0.960	0.009	109.200
I/S	1.000	0.00007		0.00005	0.600	0.005	
MEAN COAL	2.400	0.00017		0.00013	0.730	0.007	
S/S	0.430	0.00003		0.00002	0.220	0.002	
I/S	0.117	0.00001		0.00001	0.120	0.001	
3-Sep							
MAX COAL	32.100	0.00220	0.058	0.00230	13.300	0.040	335.000
S/S	4.100	0.00028		0.00029	2.840	0.008	
I/S	3.800	0.00026		0.00028	3.000	0.009	
MEAN COAL	9.490	0.00066		0.00069	3.900	0.012	
S/S	1.740	0.00012		0.00013	1.200	0.004	
I/S	1.060	0.00007		0.00008	0.850	0.003	
4-Sep							

MAX COAL	55.800	0.00380	0.064	0.00400	21.300	0.050	392.400
S/S	12.400	0.00086		0.00083	7.800	0.020	
I/S	8.900	0.00062		0.00059	6.500	0.017	
MEAN COAL	17.500	0.00120		0.00120	6.700	0.020	
S/S	3.570	0.00025		0.00024	2.300	0.006	
I/S	2.600	0.00018		0.00017	1.900	0.005	
5-Sep							
MAX COAL	178.000	0.01200	0.087	0.01900	110.980	0.069	1613.000
S/S	20.200	0.01400		0.00220	20.900	0.013	
I/S	15.100	0.00100		0.00160	18.000	0.011	
MEAN COAL	62.360	0.00400		0.00670	38.600	0.024	
S/S	6.600	0.00046		0.00072	6.860	0.004	
I/S	4.800	0.00033		0.00052	57.000	0.004	
6-Sep							
MAX COAL	0.000						
S/S	51.000	0.03500	0.096	0.00600	58.500	0.030	1983.000
I/S	23.500	0.00160		0.00280	31.000	0.016	
MEAN COAL	0.000						
S/S	9.410	0.00065		0.00110	10.700	0.005	
I/S	5.960	0.00047		0.00070	7.800	0.004	